Magnet Designs for Low Emittance Storage Rings*

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About this tutorial

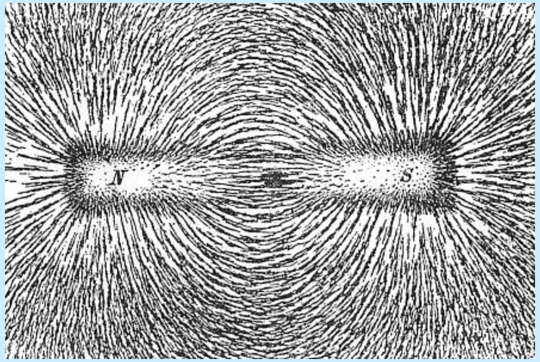
- Practically no prior knowledge about magnets is assumed.
- Although some equations are presented for reference, attempt will be made to develop concepts without explicit use of equations wherever possible.
- Only electromagnets will be discussed, although some of the concepts presented may be applicable to magnets built with permanent magnets also.
- Primary focus will be on understanding properties of magnetic field influenced by magnet designs and assembly.
- Some important design constraints and options for the new MBA-based lattice magnets will be discussed.

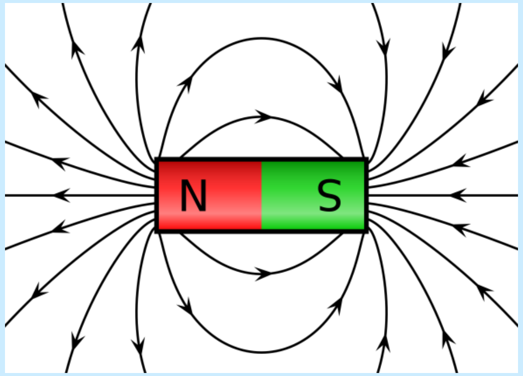
Contents

- Description of magnetic field in terms of field harmonics.
- Magnet types used in accelerators.
- Properties of magnetic field arising from symmetries in the magnet design.
- General magnet design guidelines.
- Magnet design challenges for low emittance storage rings.
  - Field strength, space constraints, gradient dipoles, cross-talk
- Magnet alignment
  - Relying solely on magnetic measurements (NSLS-II)
  - Relying solely on machining tolerances (Max-IV)

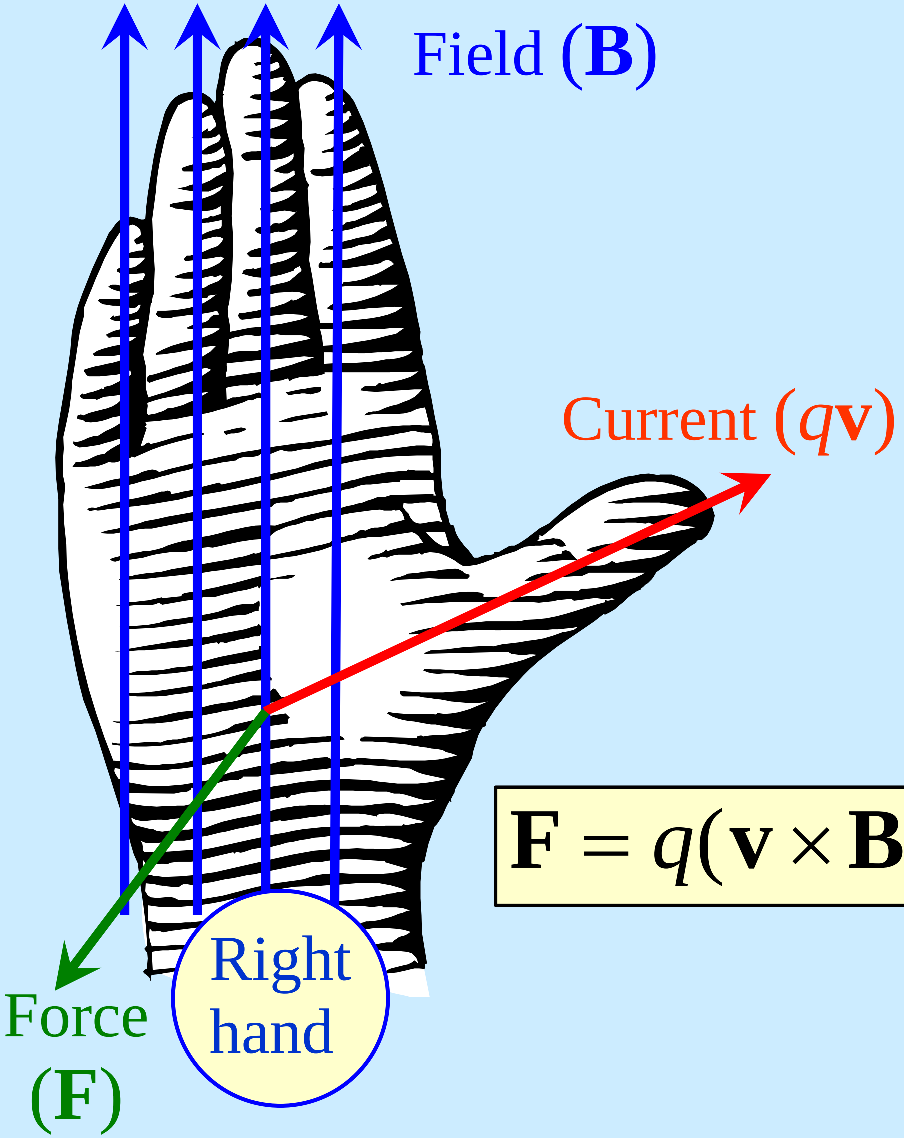
Magnetic Field Lines

- ***Magnetic field*** is a field of force produced by a magnetic material, electric currents, or changing electric fields on other magnetic materials, charged particles, or electric currents.
- Magnetic fields are detected by effects caused by such force on other materials or charges.
- Magnetic field at any given point has a ***strength***, and a ***direction***. It is, therefore, a ***vector field***.
- Magnetic ***field lines*** are a visualization of this force field.





Force on a Moving Charged Particle



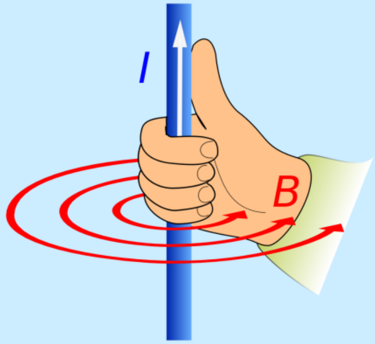
$$\mathbf{F} = q(\mathbf{v} \times \mathbf{B})$$

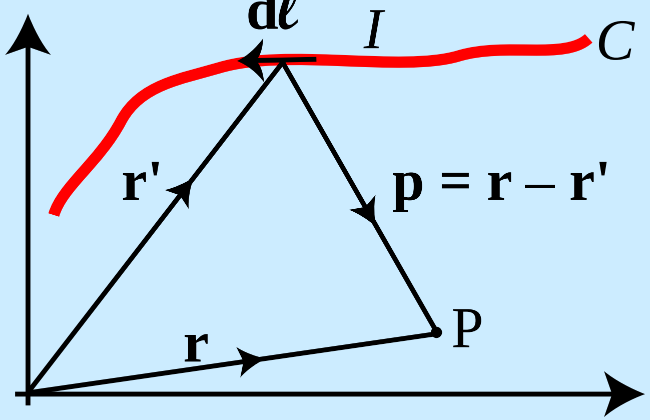
- A moving charged particle is equivalent to a current flowing in a conductor, and experiences a force in a magnetic field.
- Current direction is the direction of motion of a positive charge, or opposite to the motion for a negative charge (e.g. electrons).
- The force is directed normal to the plane formed by the field vector and the current direction.
- The force is maximum when the current is at right angles to the field, and is zero if it is along the field.

Why Use Magnets in Accelerators?

- Magnets are used in accelerators for the force they exert on a moving charged particle. This force could be used for bending or focusing the particle beam (but not to increase the energy).
- The force depends on the direction of field vector, the *velocity* of the particle (speed and direction), and the charge of the particle.
- By manipulating the strength and direction of magnetic field in a magnet, we can achieve the desired bending or focusing effect on the particle beam. $\Rightarrow$ **Primary goal of magnet Design**
- Although electric fields could also be used for bending or focusing, a much stronger magnetic force is relatively easily produced when the particle speed approaches the speed of light.
(e.g., Force in B = 0.4 Tesla equals the force in E = 1.2 x 10^8 V/m)

Producing Magnetic Fields by Currents





$$\mathbf{B}(\mathbf{r}) = \left(\frac{\mu_0}{4\pi}\right)\int_C \frac{I\,(\mathbf{d}\ell \times \mathbf{p})}{|\mathbf{p}|^3}$$

$$\mu_0 = 4\pi \times 10^{-7}\ \mathrm{T.m/A}\ (\text{or H/m})$$

- Current flowing in a conductor produces a magnetic field around it as shown qualitatively here.
- Field is stronger near the conductor and weakens as one moves away from the conductor.
- Field from any arbitrary shape and distribution of conductors can be precisely calculated using **Biot-Savart law**.
- Magnetism in magnetic materials and permanent magnets is also explained by microscopic currents and electron spin.

Fields in Free Space: Scalar Potential

- $\nabla . \mathbf{B} = 0$ ue)
- In a region free of any currents or magnetic material (e.g., in the aperture of the magnet):

$$\nabla \times \mathbf{B} = 0$$

$\mathbf{B}$ may therefore be written as the gradient of a scalar potential:

$$\mathbf{B} = \nabla \Phi_m \quad \Rightarrow \quad \boxed{\mathbf{B} \text{ field is normal to equipotential surface}}$$

- The two equations above may be combined to obtain:

$$\nabla^2 \Phi_m = 0 \qquad \boxed{\textbf{Laplace's equation for scalar potential}}$$

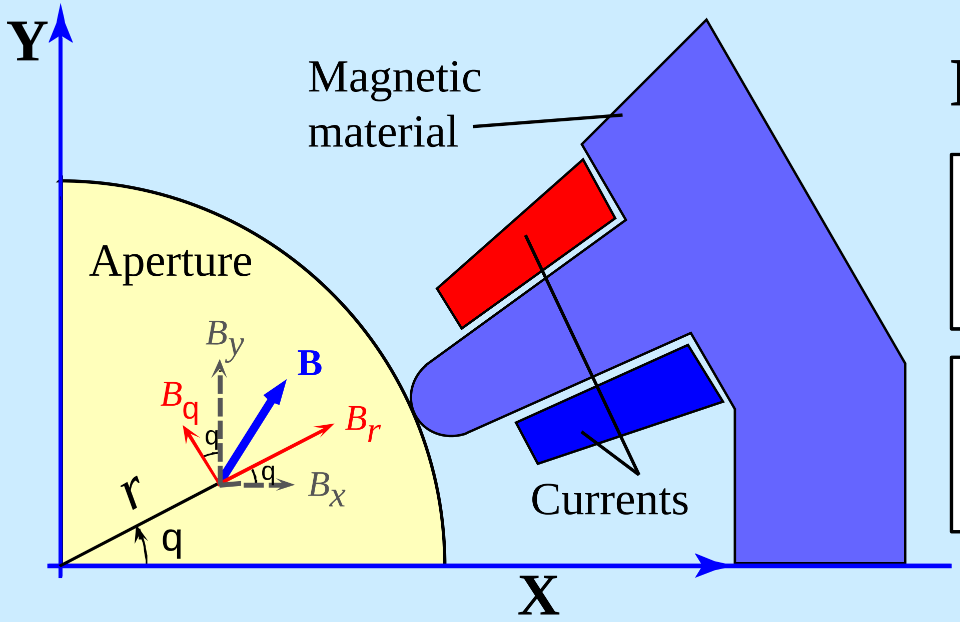
2-D Fields in Free Space

- $$\boxed{\mathbf{B} = \nabla \Phi_m} \qquad \boxed{\nabla^2 \Phi_m = 0}$$
- For very long, axially uniform magnets, the field may be considered 2-dimensional in regions away from the ends.
- For relatively short magnets, generally only the field integrated along the magnet length is of primary interest. It can be shown that the integrated field can also be described in terms of a solution of the Laplace's equation in 2 dimensions.
- The general solution for the field components in 2 dimensions can be expressed in a relatively simple ***harmonic series***.

Field Expansion in terms of Harmonics

- A point by point description of the field is not very convenient.
- The solution of Laplace's equation in 2 dimensions allows the field inside the aperture to be described as a harmonic series.
- The field (or the integrated field for short magnets) anywhere in the aperture can be calculated from a set of harmonic coefficients.
- The field distribution obtained in this way is guaranteed to satisfy Maxwell's equations.
- These harmonic coefficients can be measured very precisely in a relatively short time (< 1 min) as compared to a full field map, which could take several hours.

Cylindrical Components of Field



Inside the aperture region:

$$B_r(r,\theta) = \sum_{n=1}^{\infty} \left[B_n \sin(n\theta) + A_n \cos(n\theta) \right] \left(\frac{r}{R_{ref}} \right)^{n-1}$$

$$B_\theta(r,\theta) = \sum_{n=1}^{\infty} \left[B_n \cos(n\theta) - A_n \sin(n\theta) \right] \left(\frac{r}{R_{ref}} \right)^{n-1}$$

B_n = **2*n*-pole "Normal"** coefficient

A_n = **2*n*-pole "Skew"** coefficient

R_{ref} = **Reference radius**

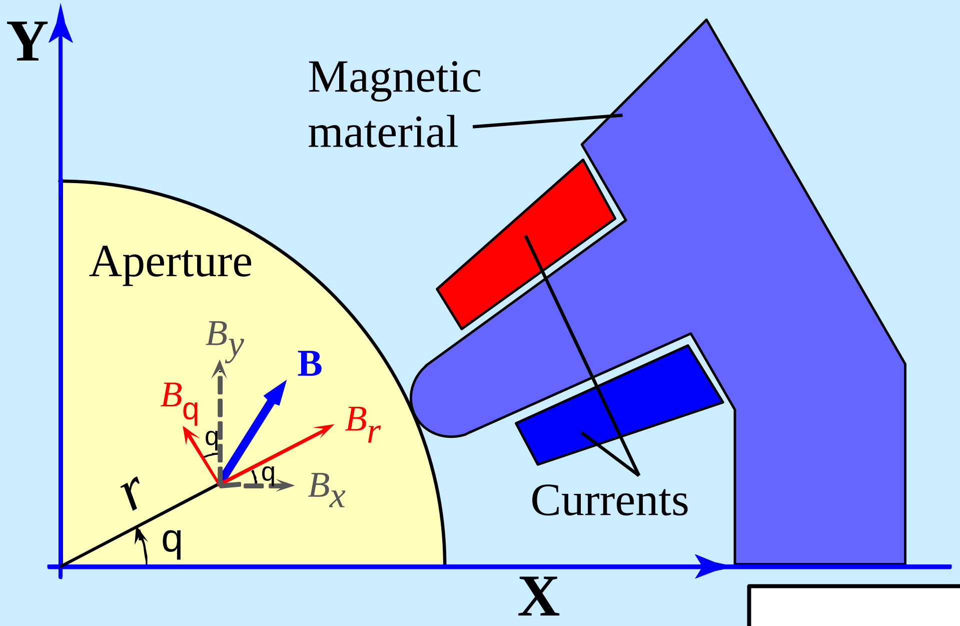
B_n and A_n are in units of Tesla (or in T.m for integral field), and scale with reference radius as R_{ref}^{n-1} .

Field contributed by the *n*-th term in the expansion is purely radial ($B_\theta = 0$) at 2*n* angular positions.

These are the angular positions of the 2*n* poles.

$$\theta_{pole}(2n\text{-pole}) = \left(\frac{1}{n}\right)\left[\tan^{-1}\left(\frac{B_n}{A_n}\right) + k\pi\right]; \quad k = 0,1,2,\ldots,(2n-1)$$

Cartesian Components of Field



B_n = **2*n*-pole "Normal"** coefficient

A_n = **2*n*-pole "Skew"** coefficient

R_{ref} = **Reference radius**

B_n and A_n are in units of Tesla (or in T.m for integral field), and scale with reference radius as R_{ref}^{n-1} .

$$B_y(r,\theta) = B_r \sin\theta + B_\theta \cos\theta$$
$$B_x(r,\theta) = B_r \cos\theta - B_\theta \sin\theta$$

$$B_y(r,\theta) = \sum_{n=1}^{\infty}\left[B_n \cos\{(n-1)\theta\} - A_n \sin\{(n-1)\theta\}\right]\left(\frac{r}{R_{ref}}\right)^{n-1}$$

$$B_x(r,\theta) = \sum_{n=1}^{\infty}\left[B_n \sin\{(n-1)\theta\} + A_n \cos\{(n-1)\theta\}\right]\left(\frac{r}{R_{ref}}\right)^{n-1}$$

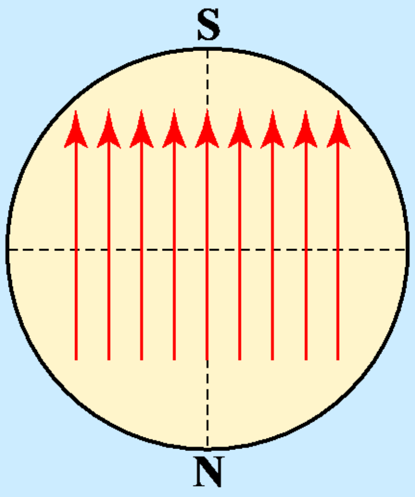
$$B_y(x,y) + iB_x(x,y) = \sum_{n=1}^{\infty}\left[B_n + iA_n\right]\left(\frac{x+iy}{R_{ref}}\right)^{n-1}$$

Examples of Pure "Normal" Fields

$$B_y(x,y) + iB_x(x,y) = \sum_{n=1}^{\infty} B_n \left(\frac{x+iy}{R_{ref}} \right)^{n-1} \quad \text{for } A_n = 0$$

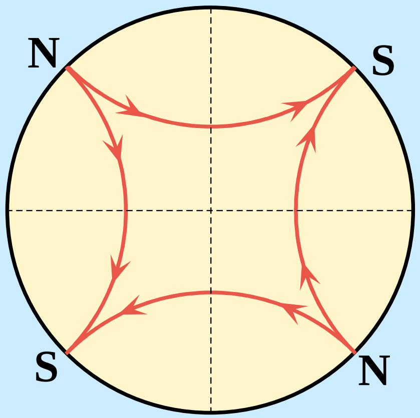
***n* = 1 (Dipole)**

$$B_y(x,y) = B_1 = \text{Constant}$$
$$B_x(x,y) = 0$$



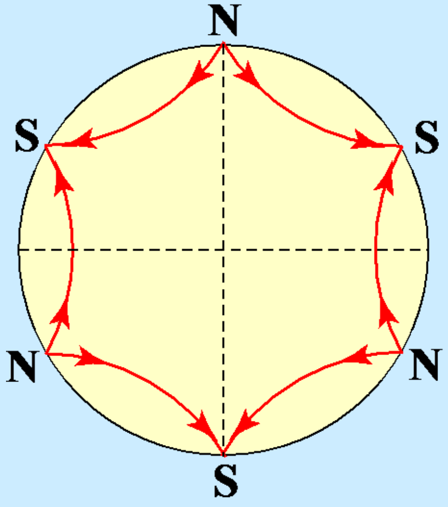
***n* = 2 (Quadrupole)**

$$B_y(x,y) = \left(B_2 / R_{ref}\right) x$$
$$B_x(x,y) = \left(B_2 / R_{ref}\right) y$$



***n* = 3 (Sextupole)**

$$B_y(x,y) = B_3 \frac{x^2 - y^2}{R_{ref}^2}$$
$$B_x(x,y) = B_3 \frac{2xy}{R_{ref}^2}$$



First pole is at θ = π/(2*n*) in this case
Poles have Top-Bottom Anti-symmetry

Examples of Pure "Skew" Fields

$$B_y(x,y) + iB_x(x,y) = \sum_{n=1}^{\infty} iA_n \left(\frac{x+iy}{R_{ref}}\right)^{n-1} \quad \text{for } B_n = 0$$

n = 1 (Skew Dipole)

$$B_y(x,y) = 0$$

$$B_x(x,y) = A_1 = \text{Constant}$$

n = 2 (Skew Quadrupole)

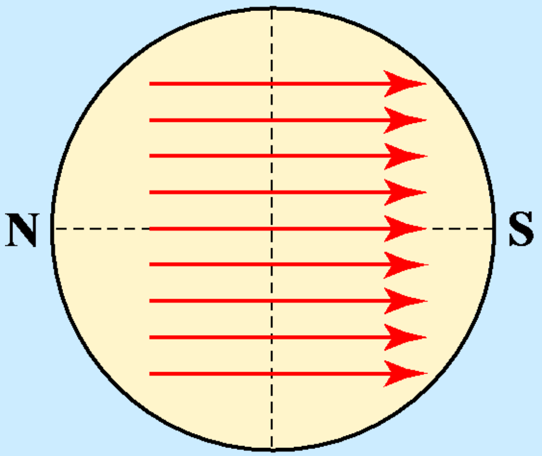
$$B_y(x,y) = -\left(A_2 / R_{ref}\right) y$$

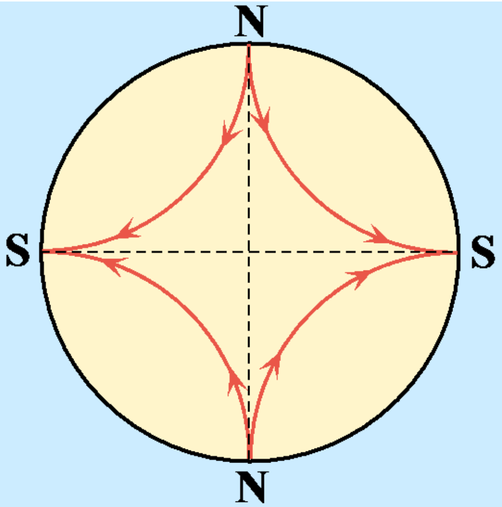
$$B_x(x,y) = \left(A_2 / R_{ref}\right) x$$

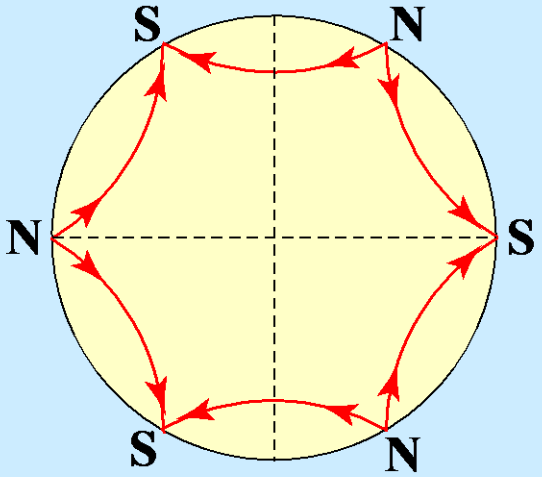
n = 3 (Skew Sextupole)

$$B_y(x,y) = -A_3 \frac{2xy}{R_{ref}^2}$$

$$B_x(x,y) = A_3 \frac{x^2 - y^2}{R_{ref}^2}$$







First pole is at θ = 0 in this case
Poles have Top-Bottom Symmetry

Interpretation in Terms of Derivatives

$$B_y(x=0;y=0)=B_1$$

$$B_x(x=0;y=0)=A_1$$

Dipole terms (n = 1) = Field at the origin

$$\left[\frac{\partial^n B_y}{\partial x^n}\right]_{x=0;y=0}=\frac{n!B_{n+1}}{R_{ref}^n};\quad n=1,2,3,\ldots$$

$$\left[\frac{\partial^n B_x}{\partial x^n}\right]_{x=0;y=0}=\frac{n!A_{n+1}}{R_{ref}^n};\quad n=1,2,3,\ldots$$

$$B_n=\frac{R_{ref}^{n-1}}{(n-1)!}\left[\frac{\partial^{n-1} B_y}{\partial x^{n-1}}\right]_{x=0;y=0};\quad n=1,2,3,\ldots$$

$$A_n=\frac{R_{ref}^{n-1}}{(n-1)!}\left[\frac{\partial^{n-1} B_x}{\partial x^{n-1}}\right]_{x=0;y=0};\quad n=1,2,3,\ldots$$

Higher order terms are proportional to higher order derivatives at the origin.

B_n and A_n scale as R_{ref}^{n-1}

The derivatives do not depend on R_{ref}.

Normalized Normal and Skew Multipoles

$$b_n = B_n / B_{ref}$$

$$a_n = A_n / B_{ref}$$

B_{ref} is a normalizing field.

b_n and a_n are dimensionless, yet depend on R_{ref}.

R_{ref} **must** be specified when quoting numbers.

- It is also common to define b_n and a_n with a multiplication factor of 10^4 on the right hand side. These are then said to be in "units".

1 "unit" = 0.01% of B_{ref}

- For a *nearly pure* multipole ($n = m$), B_{ref} is commonly chosen to be the amplitude of the main multipole component at the reference radius (this is the "desired" harmonic):

$$\boxed{B_{ref} = \left| B_m + iA_m \right|}$$

Multipoles: General Comments

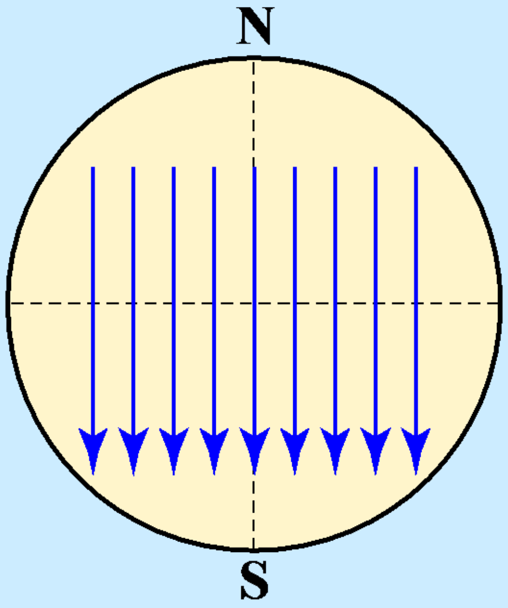
- A $2n$-pole magnet, as the name suggests, has $2n$ poles. There are alternating North and South poles, n of each, in 0-360 deg.
- B_x and B_y components have $(n–1)$ cycles in 0-360 degrees.
- B_r and B_θ components have n cycles in 0-360 degrees.
- Field strength varies as the $(n–1)^{th}$ power of radial position.
- Some count the multipoles from 0 onwards, to match the power in radial dependence. (dipole = 0, quad = 1, etc.).
- Others count the multipoles from 1 onwards, to match the number of poles of each type. (dipole = 1, quad = 2, etc.).
- A rotation by $360/n$ degrees returns a pure $2n$-pole magnet (or more precisely, the field lines in it) to its original configuration.
- A rotation by $180/n$ degrees of a pure $2n$-pole magnet interchanges the North and the South poles, and simply reverses all field line directions.

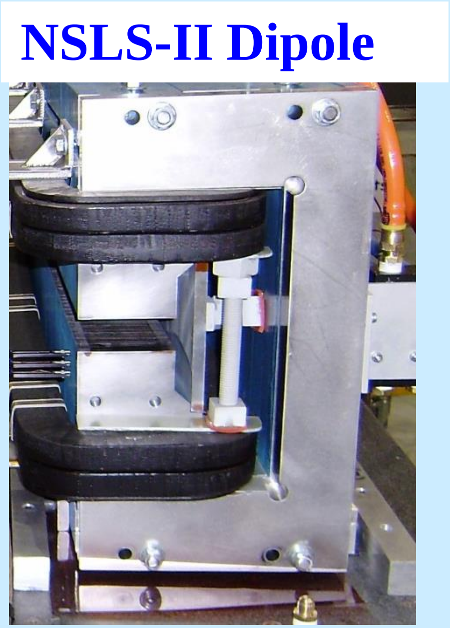
Multipoles: Normal (B_n) & Skew (A_n)

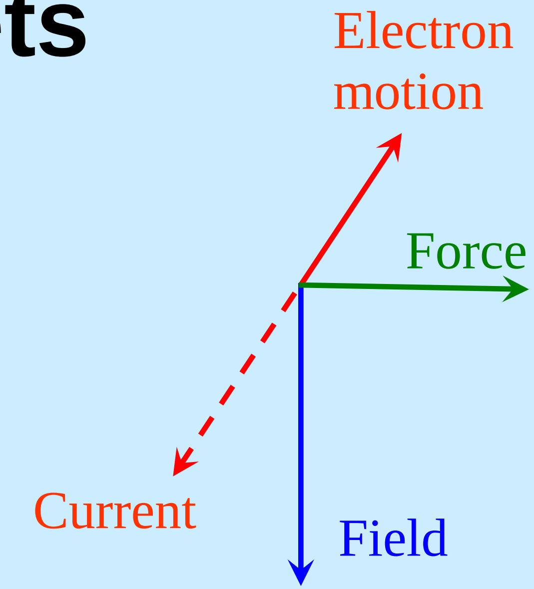
- Field on the horizontal midplane of a purely “Normal” magnet is strictly vertical. (B_n is positive if $B_y > 0$ for $x > 0$).
- Field on the horizontal midplane of a purely “Skew” magnet is strictly horizontal. (A_n is positive if $B_x > 0$ for $x > 0$).
- The poles of a “Skew” magnet start at 0^o (3’O clock), and are located every 180/n degrees in a 2n-pole magnet.
- The poles of a “Normal” magnet start at 90/n degrees, and are located every 180/n degrees in a 2n-pole magnet.
- A “Normal” (or “Skew”) magnet will change to a “Skew” (or “Normal”) magnet, as it is rotated, with a mixture of the two in between. This occurs 2n times in 0 to 360 deg.

Example: A small roll of a quadrupole produces a skew quad term.
A normal quad changes to skew quad, and vice versa, every 45 deg.

Dipole Magnets





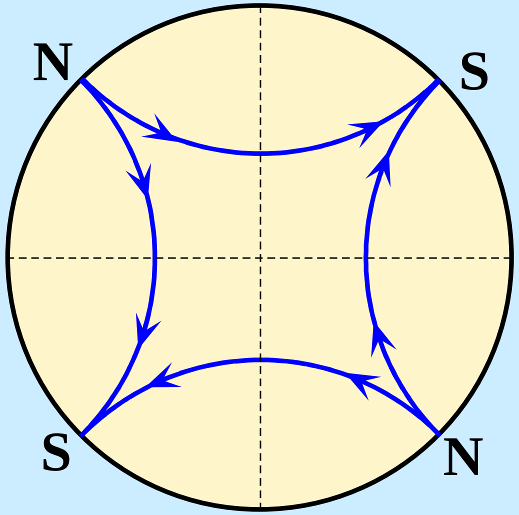


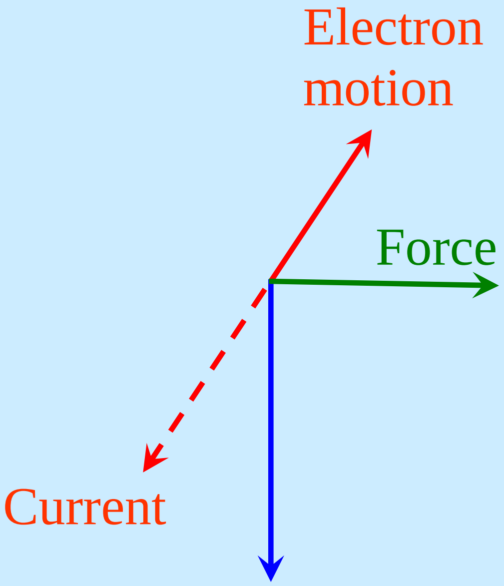
For highly relativistic unit charge:

$$\boxed{\text{Bend Radius (m)} \approx \frac{\text{Energy in GeV}}{0.3 \times \text{Field in Tesla}}}$$

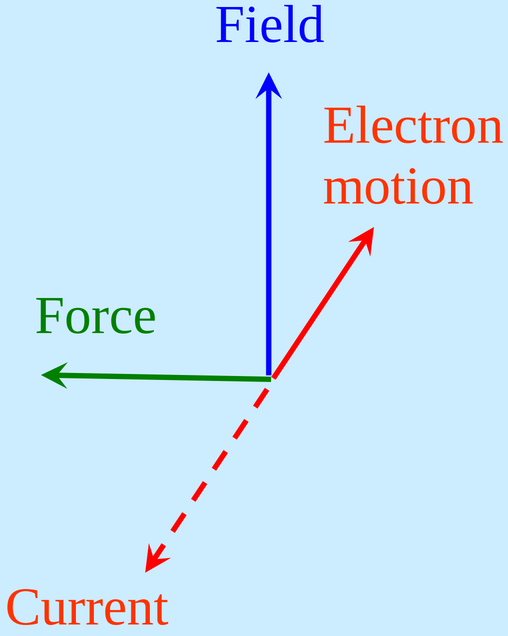
- The ***field strength and its direction are exactly the same at all points*** (fully uniform field) in the aperture of a perfect dipole magnet.
- All charged particles in a beam moving through the aperture experience a force in the same direction, regardless of their position (***the beam is bent)***.
- Particles follow a circular path in a dipole field. Radius of the circle depends on the charge and momentum of the particles, and field strength.

Quadrupole Magnets





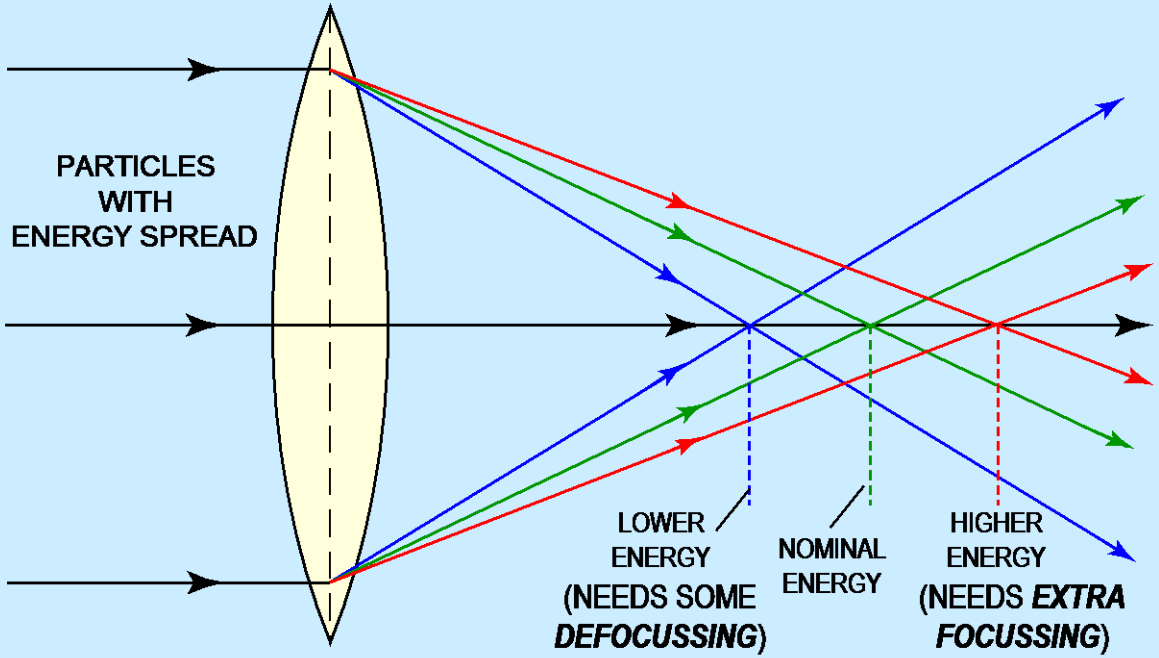
For particles on the left side



For particles on the right side

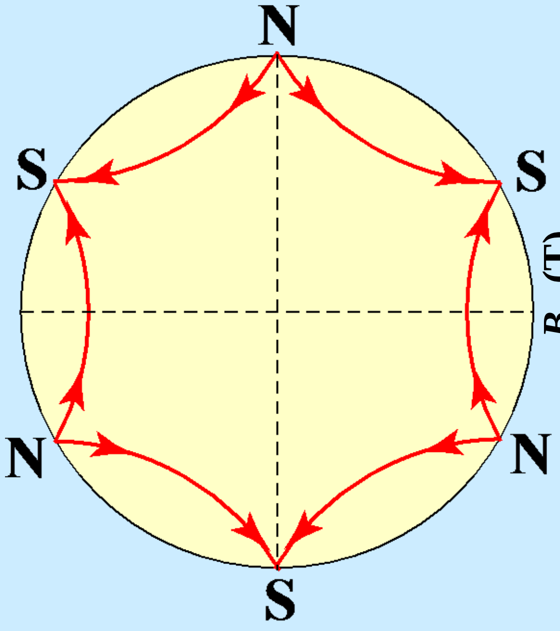
- The field strength and direction change uniformly from left to right, and from top to bottom. The field is zero on the axis.
- *The gradient* ($dB_y/dx = dB_x/dy$) *is uniform in a quadrupole magnet*.
- A gradient causes focusing in one axis, and defocussing in another.

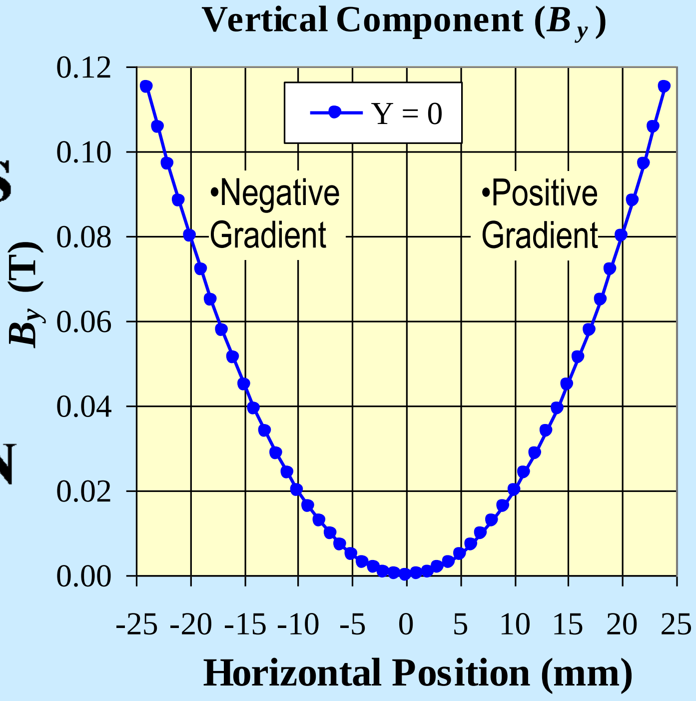
Quadrupole Magnets: Chromatic Error

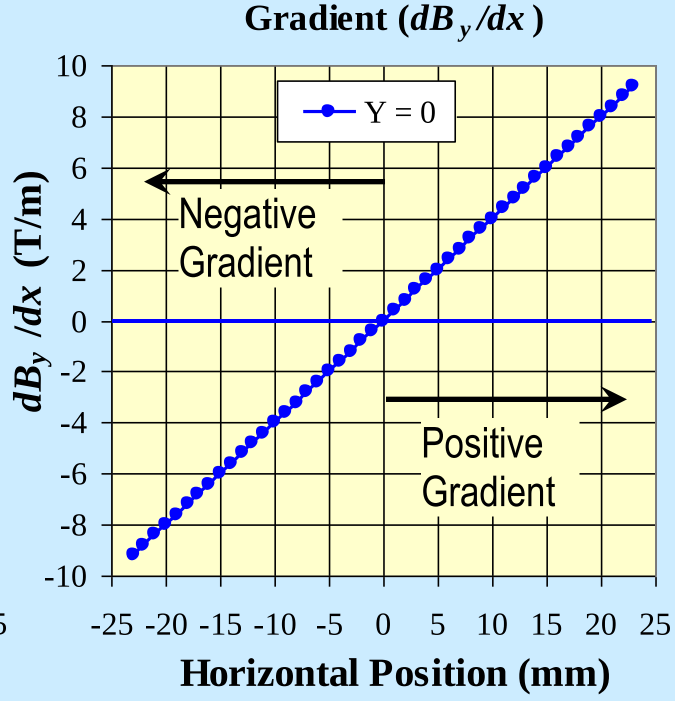


- The force exerted on all particles passing at the same location in a quadrupole is nearly the same, regardless of energy (*for relativistic case and small* ΔE).
- The same force, however, bends particles of different energies by different angles, causing the equivalent focal length to depend on energy.
- We need to provide more, or less, focusing depending on energy.

Sextupole Magnets

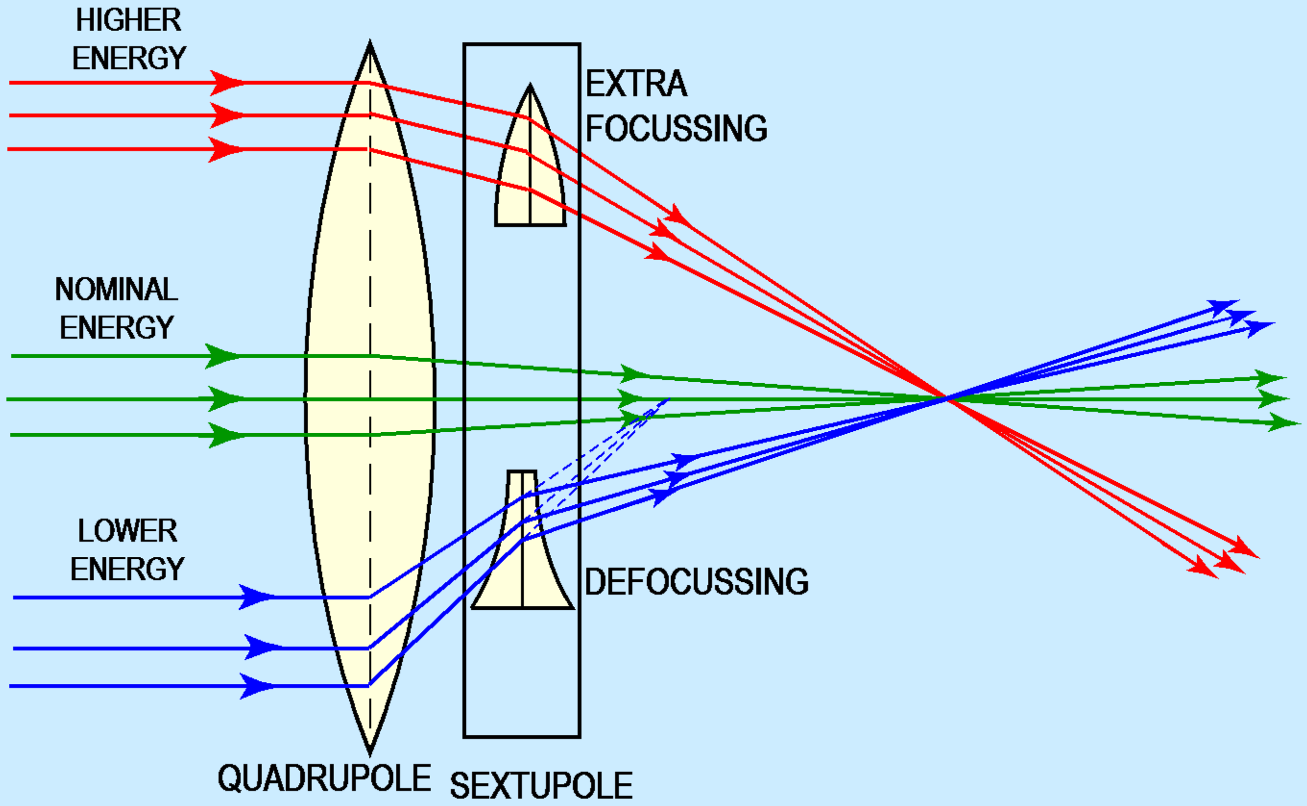






- The ***field strength varies as square of the radial position***.
- In other words, ***the second derivative of field*** (d^2B_y/dx^2) ***is uniform in a sextupole magnet***, or the ***gradient*** (dB_y/dx) ***varies linearly with position***.
- Particles on one side of the center see a focusing gradient, those on the other side see a defocussing gradient. Magnitude of gradient increases with offset.

Sextupoles: Chromatic Error Correction



If a sextupole is placed in a location where the particles are separated in position according to their energy (*non-zero dispersion*), the focusing strengths for the high and low energy particles can be compensated such that all particles are focused at the same point.

Field Distribution in a Real Magnet

- One way to describe the field distribution in a real magnet is to give all the field components at a large number of points in the region of interest (Field Map).
- In general, the field components will have an arbitrary variation with angle for a given radius.
- Any such arbitrary variation can be decomposed into pure sine and cosine functions (Fourier components) with zero, one, two, …. cycles in 0 to 360 degrees. Each of these components represents a pure normal or a skew ***multipole*** (dipole, quadrupole, etc.), or ***harmonic***.
- The field can be fully described for all values of (x,y) in the aperture by just a few numbers (strengths of various normal and skew multipoles), instead of a large field map.

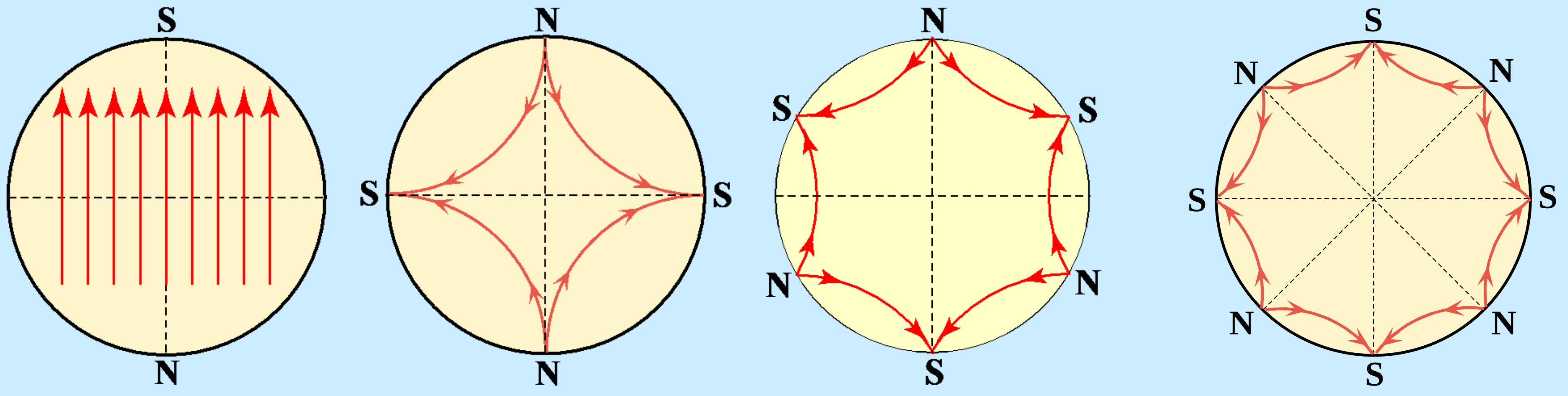
Field Quality

- In an accelerator magnet, one desires the field to have a particular multipolarity depending on the function to be performed by the magnet (bending, focussing, …)
- In reality, the as-built magnets have other “unwanted” multipole components, either due to design limitations, or due to construction errors.
- The relative strengths of the “unwanted” and the “wanted” multipoles defines the field quality. Lower relative strengths of “unwanted” multipoles mean a better “field quality”.
- The strengths of the “unwanted” harmonics normalized to the “wanted” multipole, when expressed as parts in 10,000, are said to be in “units”. **Thus one “unit” of a multipole means a strength of 0.01%, or 100 ppm of the strength of the “wanted” multipole at the stated radius (reference radius). Typical requirements are < 1-10 units.**

Symmetries & Allowed Harmonics

- A single current element, or a magnetic pole at an arbitrary angular position and radius produces field consisting of ***all*** multipoles.
- Accelerator magnets often have definite symmetries (or antisymmetries) in the current distribution or pole profiles. These symmetries lead to cacellations of some multipoles, and only certain multipoles survive. Those that survive are known as the ***allowed harmonics***.
- To obtain a pure multipole, the current distribution (or the iron shape in the case of iron dominated magnets) must be further designed in such a way that only ONE of the allowed harmonics survives.
- Real, as-built magnets have all multipoles (although small) due to either design limitations, or construction errors. These ***error terms*** give clue as to what type of symmetry is broken.

Symmetry in Harmonic Fields (1)

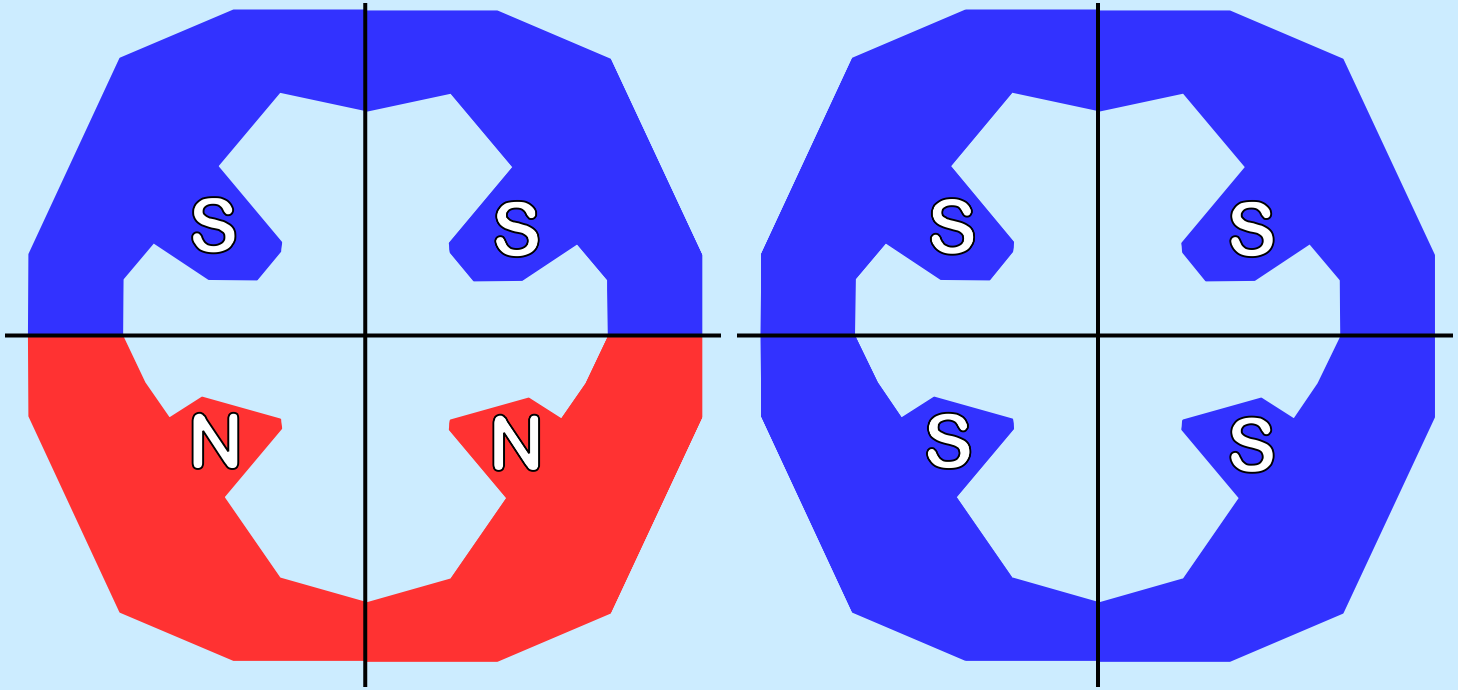


Normal Dipole (B_1) Skew Quadrupole (A_2) Normal Sextupole (B_3) Skew Octupole (A_4)

Fields from ODD NORMAL and EVEN SKEW harmonics look the same when viewed from either end of the magnet.

Poles have a Left-Right Symmetry in this case

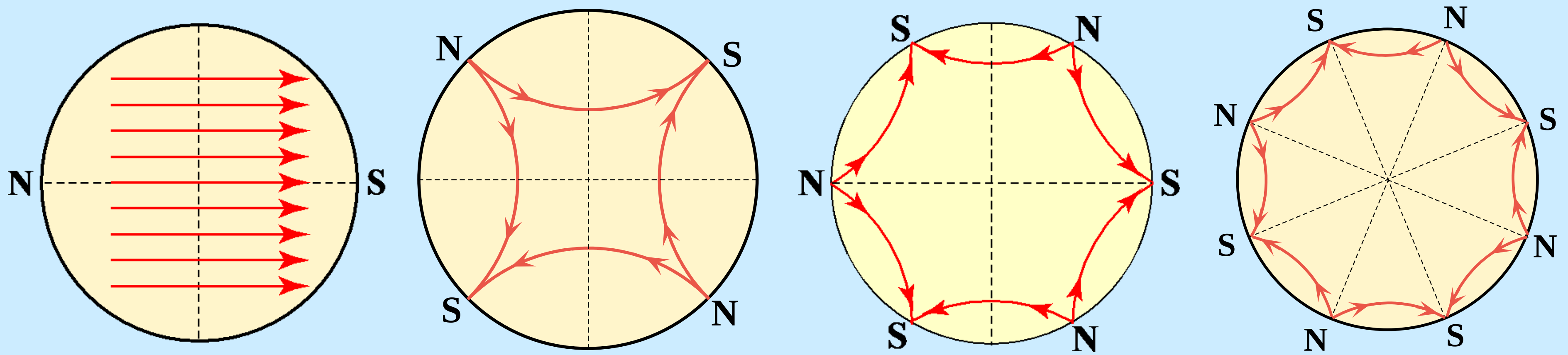
Left-Right Symmetry in Poles



Symmetry = Mechanical symmetry + Polarity Symmetry

- Magnet looks the same when viewed from the opposite end
- Only the ODD NORMAL and EVEN SKEW terms are allowed (B_1, A_2, B_3, A_4, B_5, A_6, ….)

Symmetry in Harmonic Fields (2)

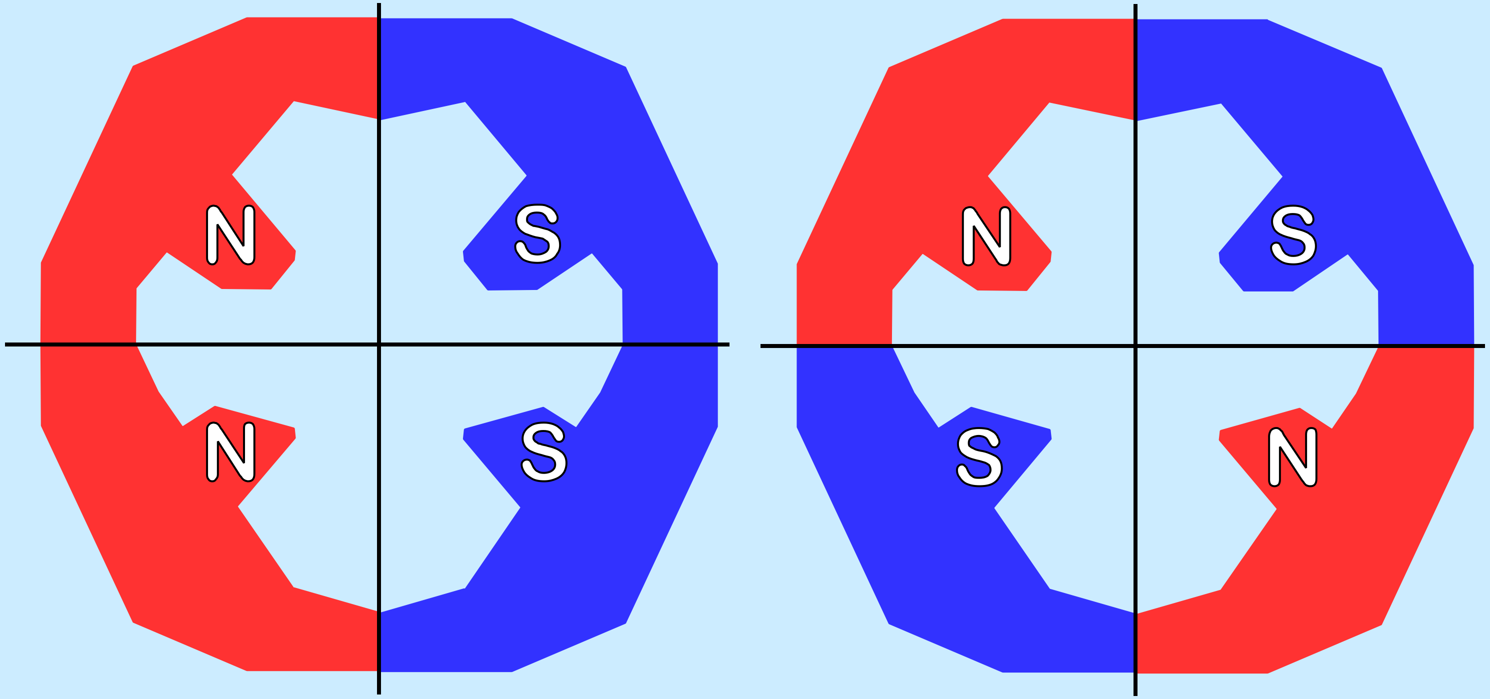


Skew Dipole (A_1) Normal Quadrupole (B_2) Skew Sextupole (A_3) Normal Octupole (B_4)

Fields from ODD SKEW and EVEN NORMAL harmonics look reversed when viewed from the other end of the magnet.

Poles have a Left-Right *Anti*-Symmetry in this case

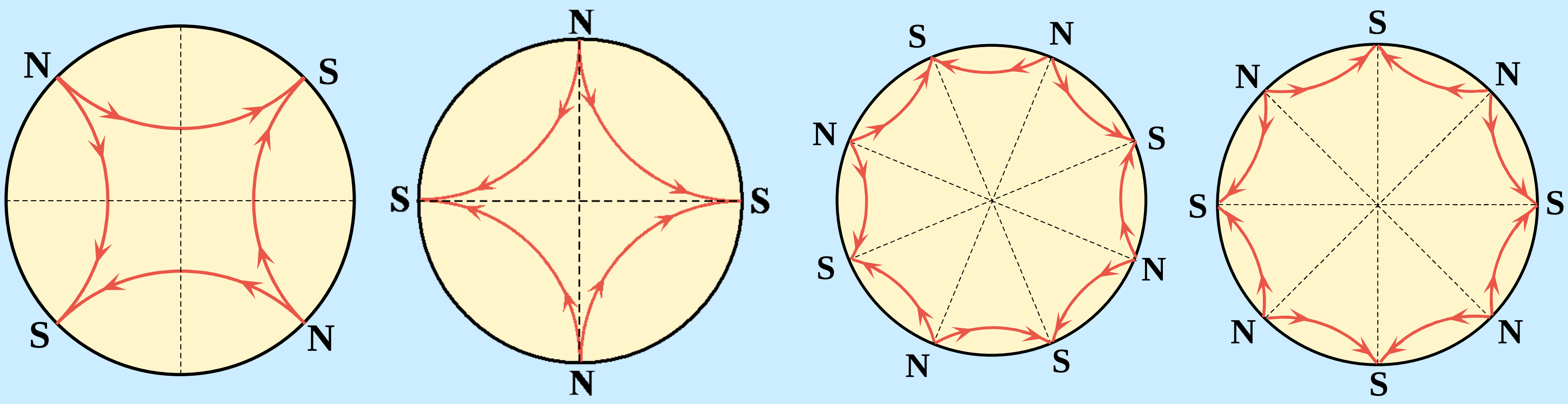
Left-Right Anti-Symmetry in Poles



Anti-Symmetry = Mechanical *symmetry* + Polarity Anti-Symmetry

- Field lines should reverse when viewed from the opposite end
- Only the EVEN NORMAL and ODD SKEW terms are allowed (A_1, B_2, A_3, B_4, A_5, B_6, ….)

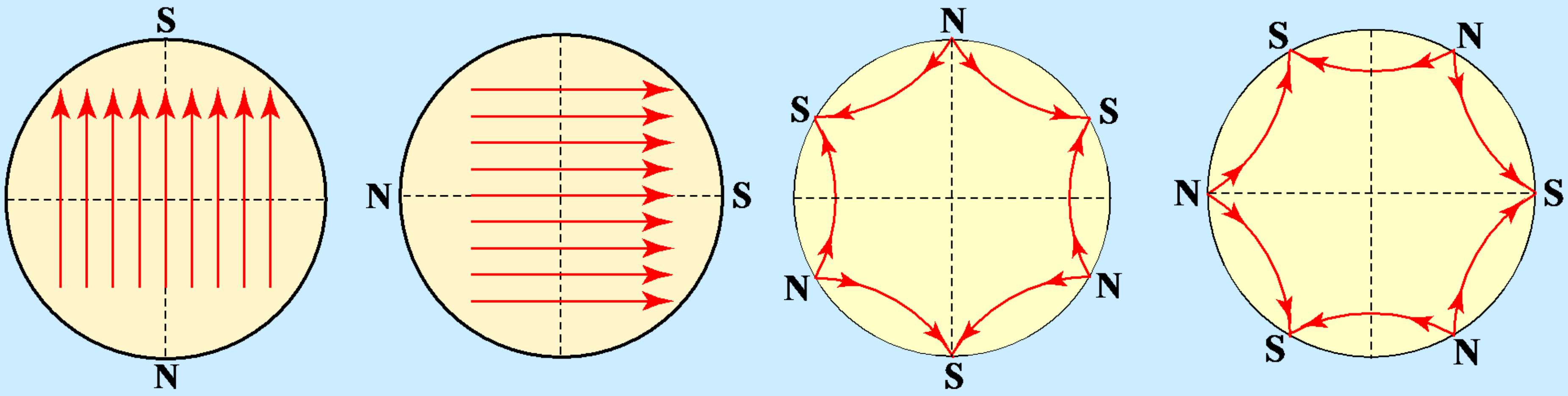
Symmetry in Harmonic Fields (3)



Normal Quadrupole (B_2)   Skew Quadrupole (A_2)   Normal Octupole (B_4)   Skew Octupole (A_4)

Fields from ALL EVEN (NORMAL & SKEW) harmonics look the same if the magnet is rotated by 180 degrees (upside down).

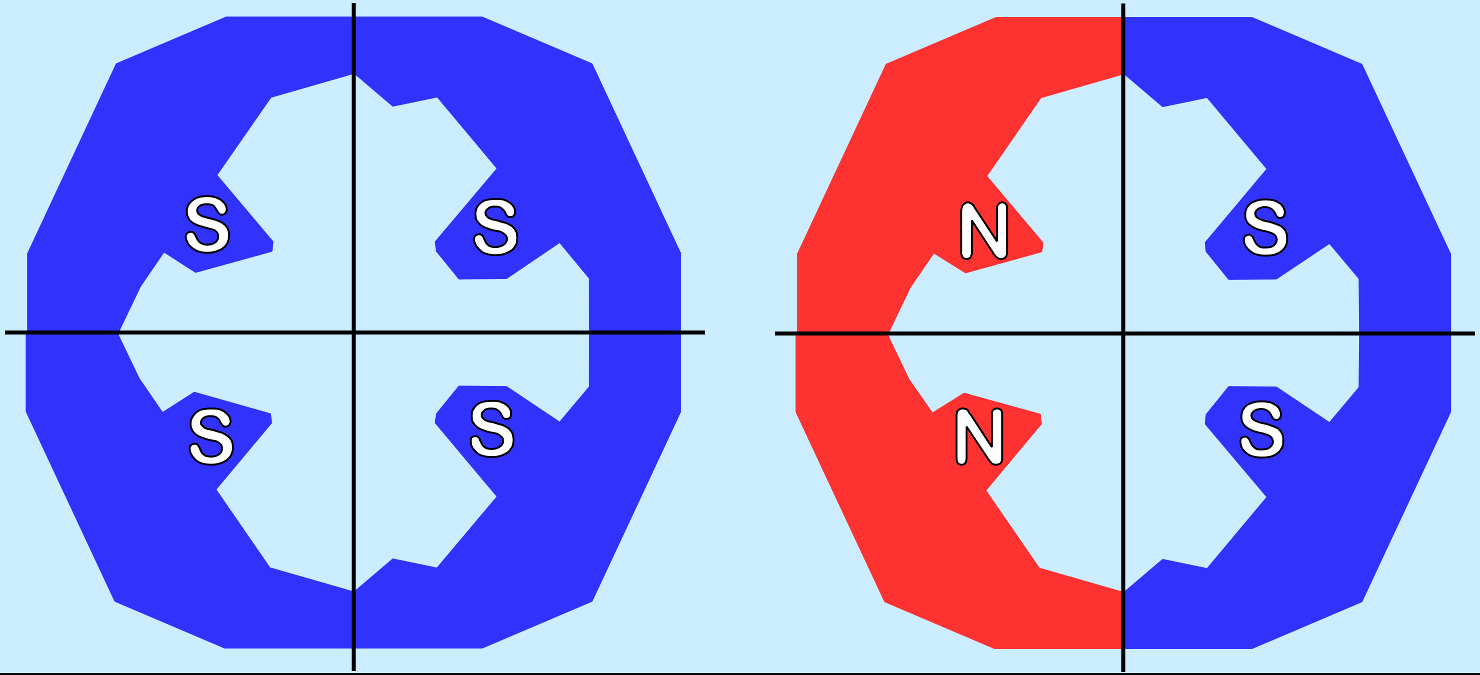
Symmetry in Harmonic Fields (4)



Normal Dipole (B_1) Skew Dipole (A_1) Normal Sextupole (B_3) Skew Sextupole (A_3)

Fields from ALL ODD (NORMAL & SKEW) harmonics look reversed if the magnet is rotated by 180 degrees (upside down).

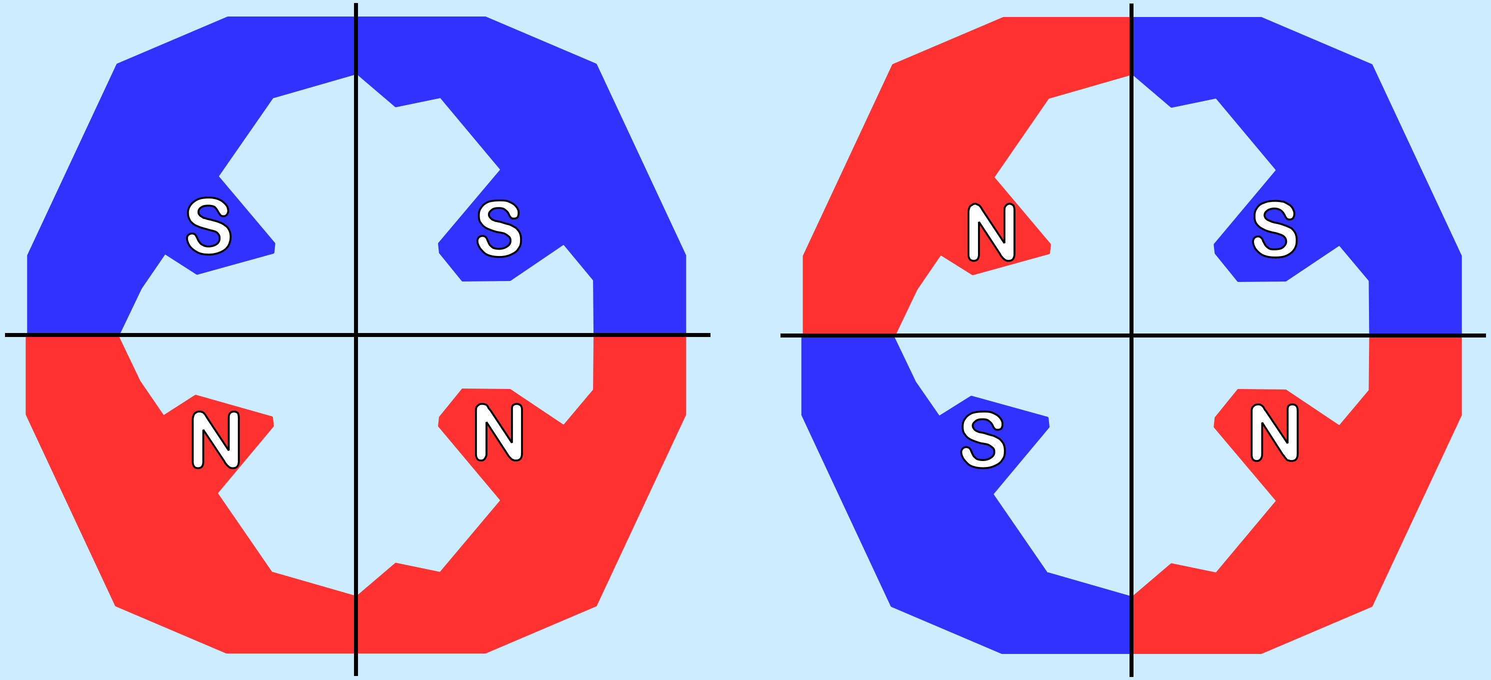
Top-Bottom Symmetry in Poles



Symmetry = Mechanical symmetry + Polarity Symmetry

- Magnet looks the same when rotated 180 degrees and then viewed from the opposite end.
- Only the SKEW terms are allowed $(A_1, A_2, A_3, A_4, A_5, A_6, \ldots.)$

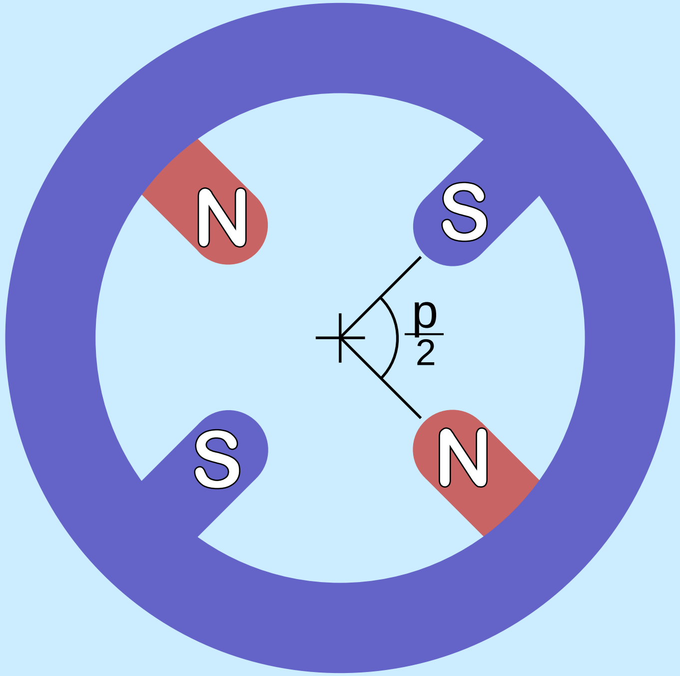
Top-Bottom Anti-Symmetry in Poles



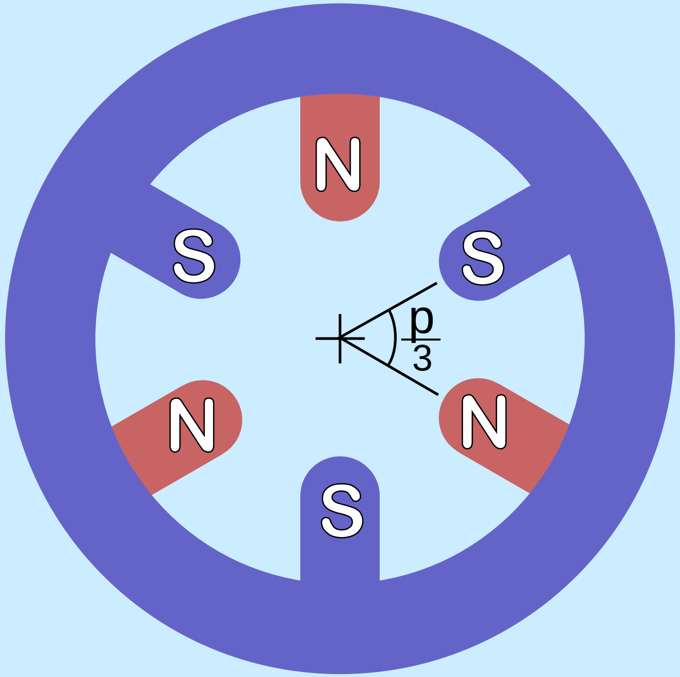
Anti-Symmetry = Mechanical *symmetry* + Polarity Anti-Symmetry

- Magnet polarity looks reversed when rotated 180 degrees and then viewed from the opposite end.
- Only the NORMAL terms are allowed $(B_1, B_2, B_3, B_4, B_5, B_6, \ldots.)$

Rotational Symmetry



$n = 2, 6, 10, 14, 18, \ldots$ only



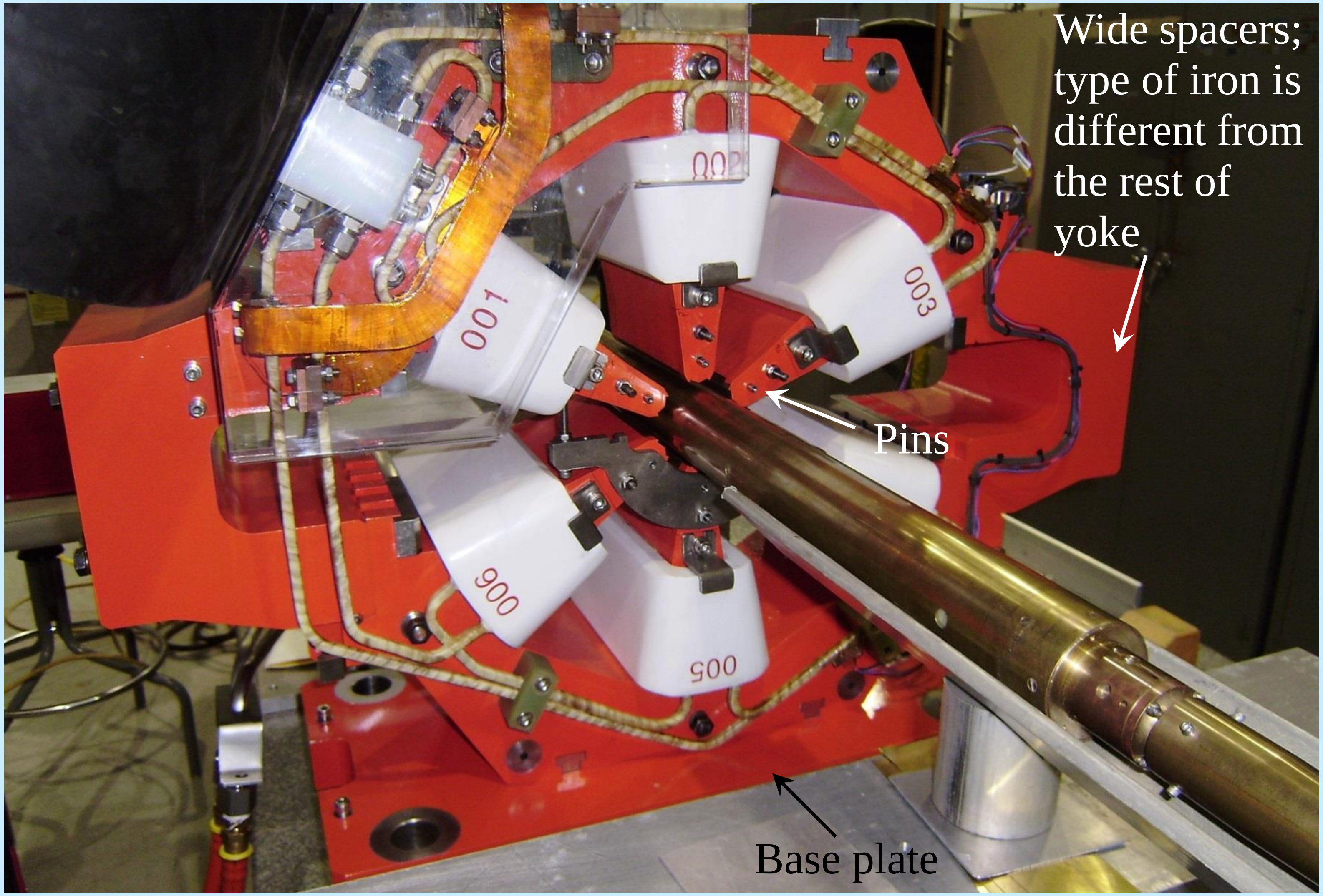
$n = 3, 9, 15, 21, 27, \ldots$ only

- In a $2m$-pole magnet, the magnet polarity looks reversed when rotated by π/m (m = 1: Dipole; m = 2: Quadrupole, etc.).
- Only harmonics that are ODD MULTIPLES of m are allowed.

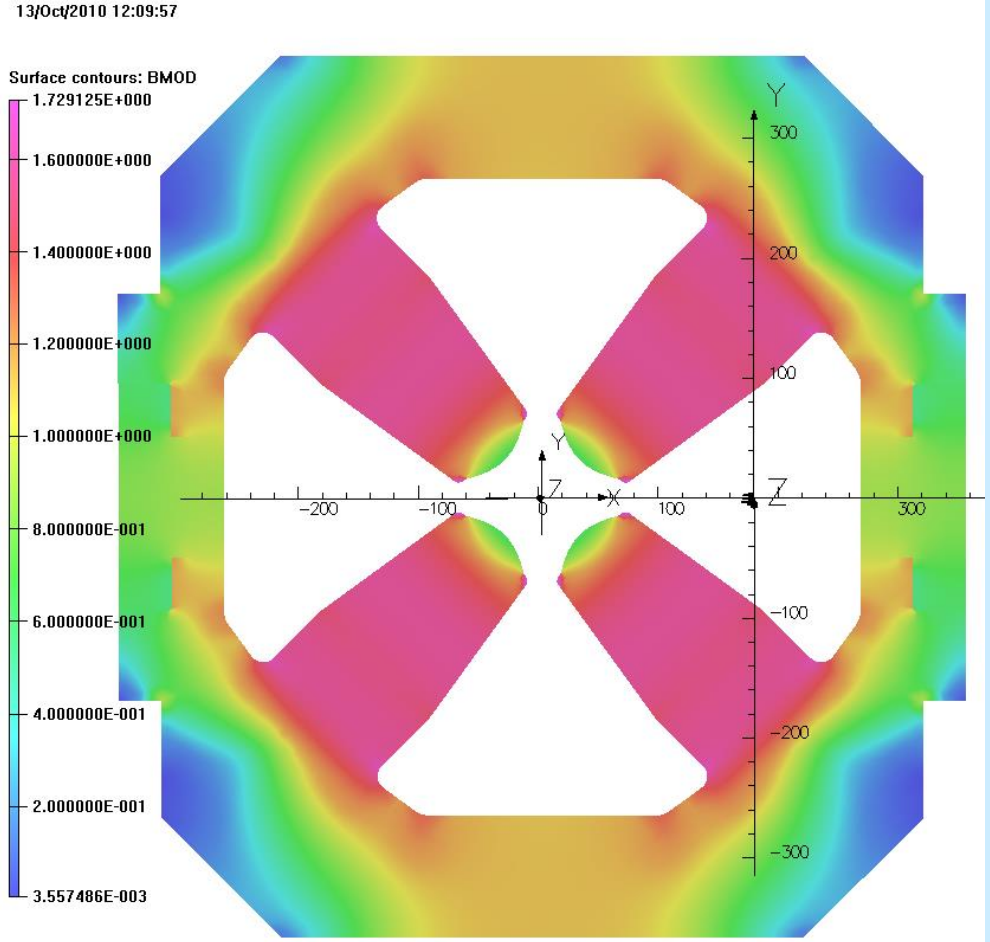
What affects Field Quality in a Magnet?

- Even a perfectly symmetric magnet has many *allowed* harmonics, out of which only one is of interest. The *unwanted, but allowed* terms must be minimized by design.
- The first limitation to field quality comes from design limitations, as not all of the *unwanted, but allowed* harmonics can be made exactly zero in a practical magnet due to other design constraints and requirements.
- Further degradation of field quality occurs due to loss of exact symmetries, and deviations from the design, due to both systematic and random construction errors. In general, all normal and skew harmonics are generated to some extent. However, certain harmonics may be prominent if a particular symmetry is broken to a larger extent. Such harmonics may aid in diagnosing problems.
- Field quality can also degrade due to ***iron non-uniformities***, or due to ***non-uniform iron saturation*** at high fields.

Design Non-symmetry: Wide Sextupole



Non-uniform Saturation of Iron Yoke



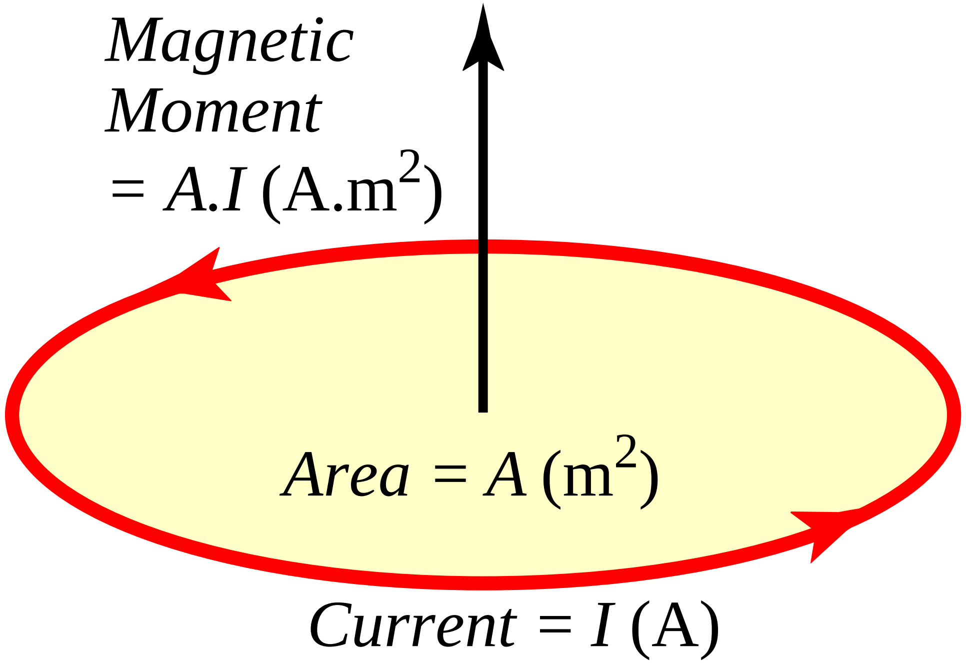
(*from Charles Spataro, BNL*)

- Field strength is not the same at all points in the yoke. Different parts of the yoke thus saturate differently.
- If at least the basic magnet rotational symmetry is maintained, no unallowed harmonics are generated by saturation. Only the allowed terms may change at high fields.
- If the iron is not symmetric all around, the basic magnet rotational symmetry is broken, causing unallowed terms to also appear.
- Control of magnetic properties of yoke material is also critical, in addition to required precision in manufacturing and assembly.

Magnetic Materials: **B** & **H** Fields

- A current carrying conductor produces a magnetic field.
- Microscopic domains in a ferromagnetic material grow, and get aligned in this field, resulting in a ***magnetization*** of the magnetic material.
- The total field, **B**, is a sum of what is generated by the external currents, and by the agglomeration of tiny magnets in the magnetic material.
- The **H** field is a field defined for convenience in order to take into account, in an average way, the contributions from atomic currents in the magnetic material.
- The **H** field in a magnetic material scales with current, the **B** field may be non-linear, depending on the material properties.

B & H Fields: Definitions



Magnetization, **M** =
Magnetic Moment/volume (A/m)

$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$$

$$\mathbf{B} = \mu_0\mu_r\mathbf{H}$$

μ_0 = Permeability of free space *

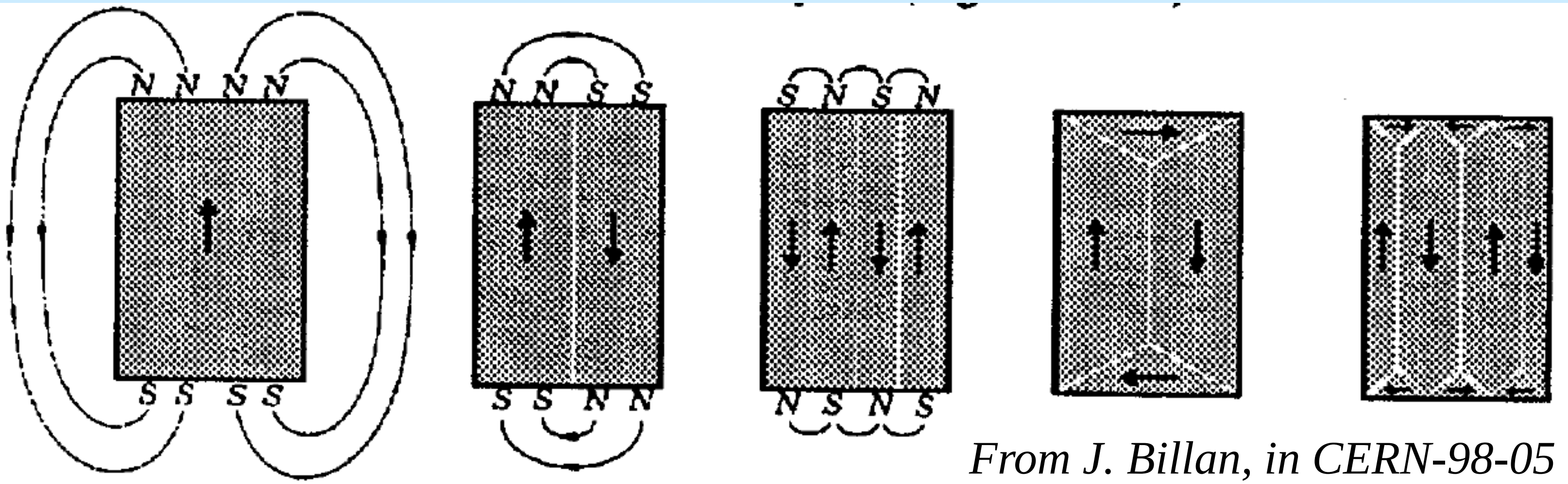
$= 4\pi \times 10^{-7}$ T.m/A (or H/m)

μ_r = Relative Permeability

B and **H** are the same in free space, except for a factor μ_0 to change units.

**The value of μ_0 follows from the standard definition adopted for Ampere.*

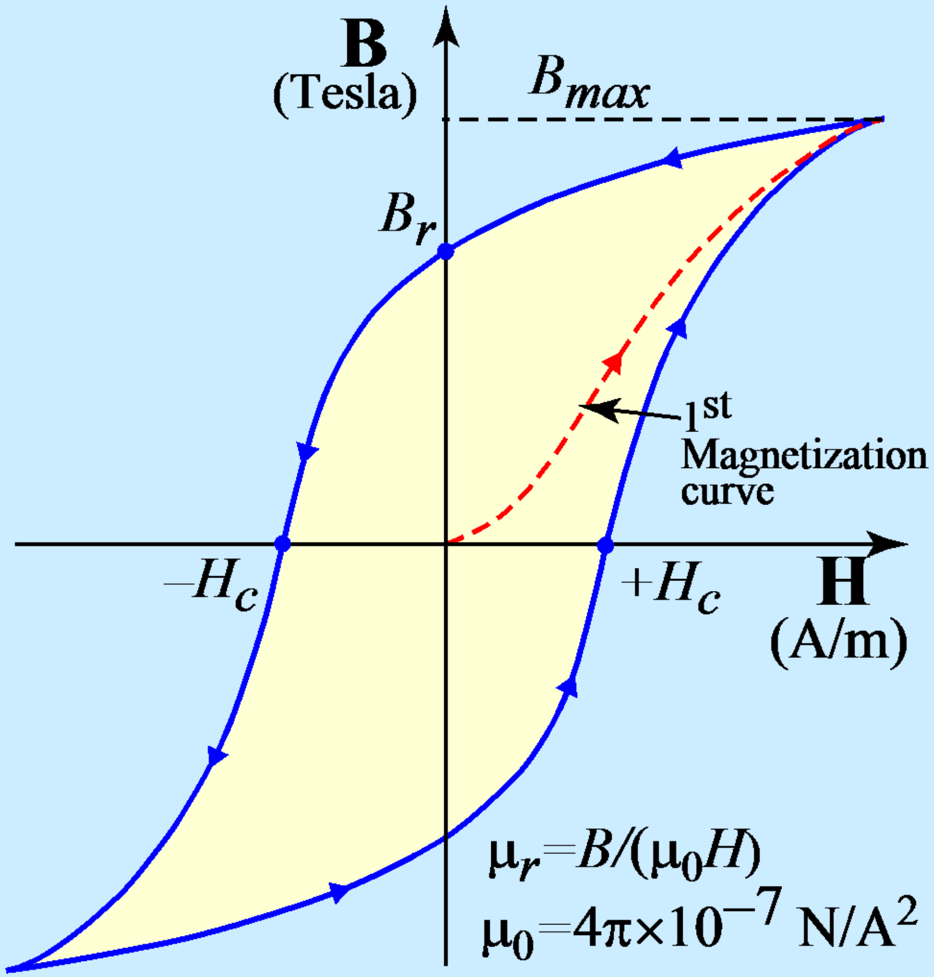
Magnetic Domains



From J. Billan, in CERN-98-05

- Energy is minimized by breaking up a bulk magnetic material into smaller domains, which are aligned in different directions, such that the net magnetization at bulk level is zero in a completely demagnetized sample, even though the magnetization in each domain is equal to the saturation magnetization.
- In the presence of external magnetic field, the domains which are not aligned with the field will tend to align themselves to minimize energy. This happens by growth of aligned domains at low fields, and by rotation of domains at higher fields.
- The microstructure of the material influences the process of domain growth and alignment, thus affecting the magnetic properties of the material.

B-H Curve



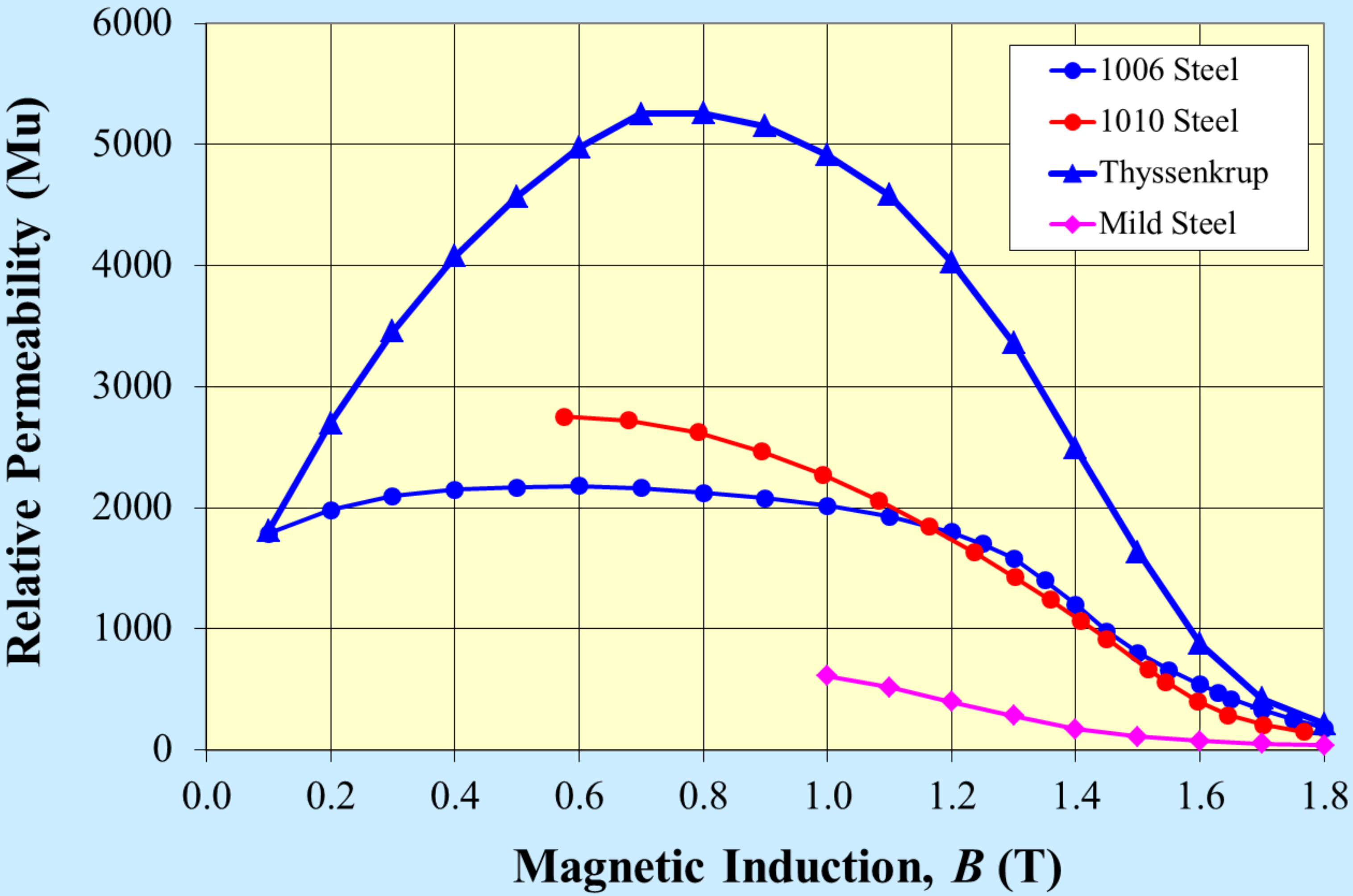
H_c = Coercivity

B_r = Remnant Field

Some correlation exists between H_c and the maximum permeability.

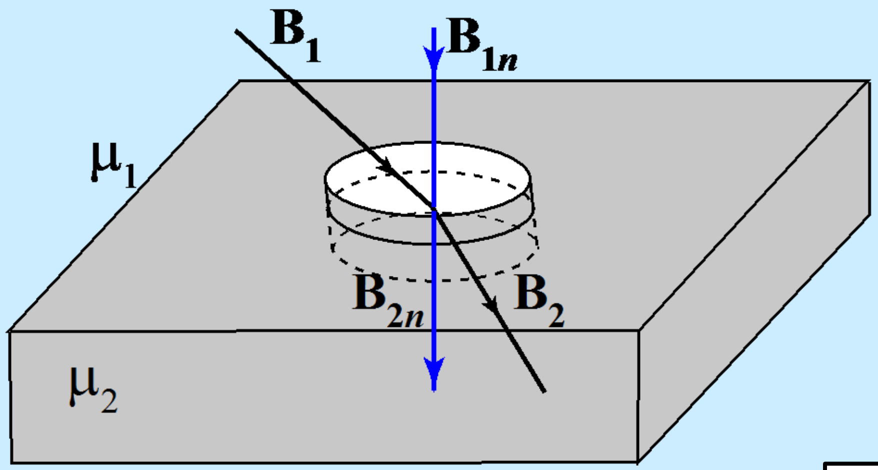
Coercivity and permeability are sensitive to material history, such as cold work, grain size, etc.

Variation of Permeability with Field



(*Based on data from Charles Spataro, BNL*)

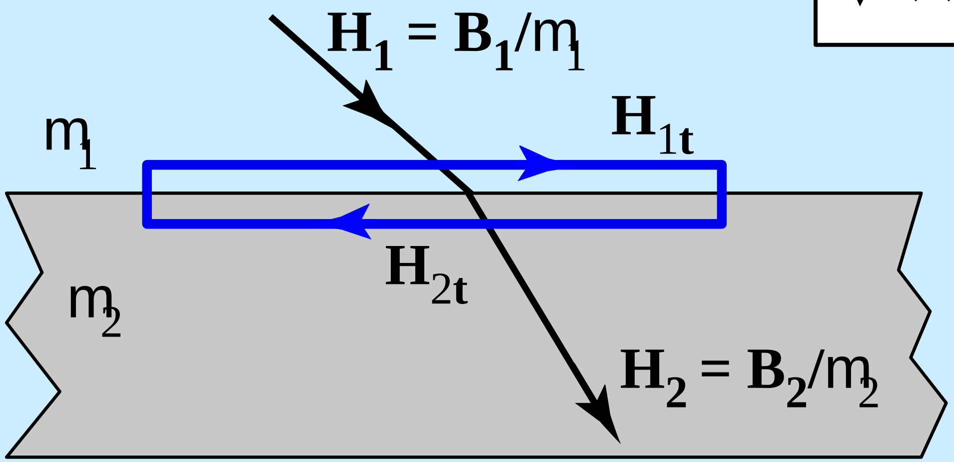
Boundary Conditions



$$\boxed{\nabla \cdot \mathbf{B} = 0}$$

The normal component of **B** is the same on both sides:

$$\mathbf{B}_{1n} = \mathbf{B}_{2n}$$



$$\boxed{\nabla \times \mathbf{H} = \mathbf{J}\ \text{(current density)}}$$

For **J** = 0, tangential component of **H** is the same on both sides: $\mathbf{H}_{1t} = \mathbf{H}_{2t}$

For $\mu_2 \to \infty$, $\mathbf{H}_{1t} = \mathbf{H}_{2t} = \mathbf{0}$

(Field is normal to surface)

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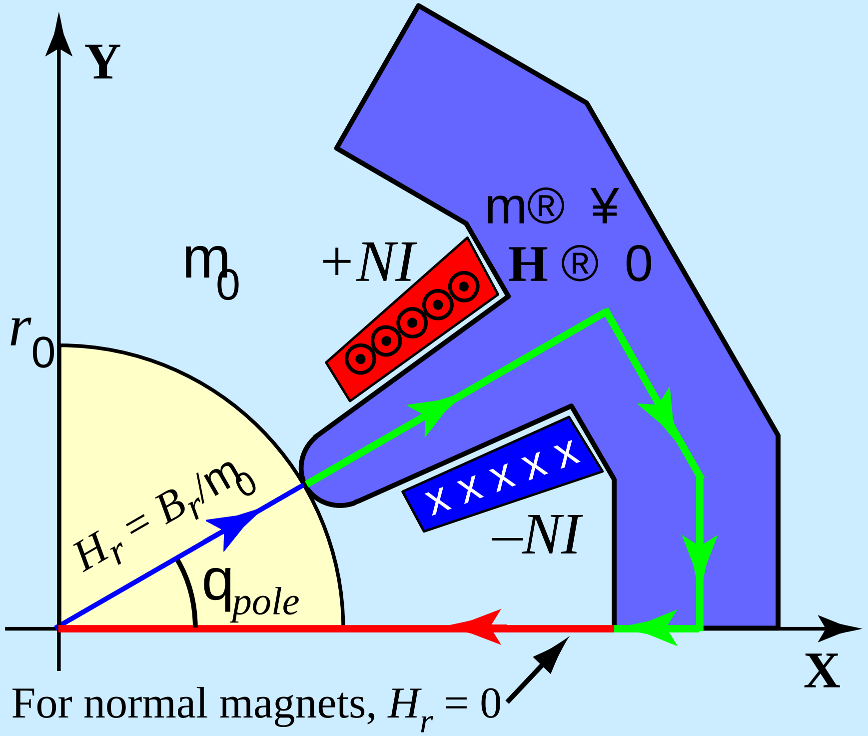
Specifying Magnet Requirements

- **Type of magnet (Dipole, quadrupole, etc.)**
- **Required physical aperture**
- **Strength required (typically integrated field for short magnets)**
- **Field quality specifications (harmonics, reference radius)**
- Physical space available (longitudinal and transverse)
- Interface with vacuum and beamline components
- Electrical specifications (current, voltage, inductance, …)
- Cooling (pressure drop, flow rate, temperature rise)
- Impact on (or from) neighboring magnets/other components
- Reproducibility under dis-assembly/reassembly
- Safety, radiation resistance, reliability, …

Calculating Ampere Turns Needed



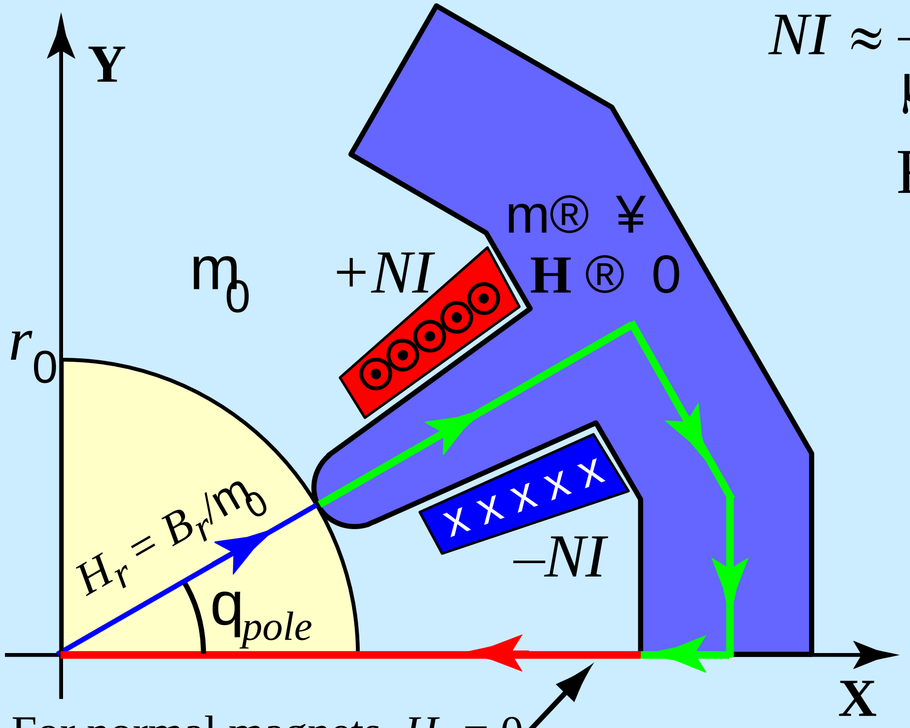
$$\oint \mathbf{H}.d\ell = NI = \text{Ampere.turns/pole}$$

- For very high permeability, **H** is nearly zero inside the iron yoke.
  (Green segment contribution ~ 0)
- For a purely "normal" magnet (no skew components), field is normal to the midplane.
  (Red segment contribution = 0)
- For integral along the depicted closed path, only the blue segment contributes significantly:

$$\int_0^{r_0} B_r(r,\theta_{pole})dr \approx \mu_0 NI$$

Calculating Ampere Turns Needed (2)

$$NI \approx \frac{1}{\mu_0}\int_0^{r_0} B_r(r,\theta_{pole})dr : \text{Ampere.turns/pole}$$



For normal magnets, $H_r = 0$

For a pure $2n$-pole, normal magnet:

From Slide 10:

$$B_r(r,\theta_{pole}) = B_n \sin(n\theta_{pole})\left(\frac{r}{R_{ref}}\right)^{n-1}$$

From Slide 10:

$$\theta_{pole} = \frac{\pi}{2n} \Rightarrow \sin(n\theta_{pole}) = 1$$

$$B_n = \frac{R_{ref}^{n-1}}{(n-1)!}\left[\frac{\partial^{n-1}B_y}{\partial x^{n-1}}\right]_{x=0;y=0} \quad \text{(From Slide 14)}$$

$$B_r(r,\theta_{pole}) = \frac{r^{n-1}}{(n-1)!}\left[\frac{\partial^{n-1}B_y}{\partial x^{n-1}}\right]_{x=0;y=0}$$

$$NI \text{ (per pole)} \approx \frac{r_0^n}{n!\mu_0}\left[\frac{\partial^{n-1}B_y}{\partial x^{n-1}}\right]_{x=0;y=0}$$

Calculating Ampere Turns Needed (3)

$$NI\text{ (per pole)} \approx \frac{r_0^n}{n!\mu_0}\left[\frac{\partial^{n-1}B_y}{\partial x^{n-1}}\right]_{x=0;y=0}$$

(Pure $2n$-pole magnet)

Type of Magnet	Ampere.turns/pole
Dipole	$\frac{B_0 r_0}{\mu_0} \approx 8000 \cdot B_0(\mathrm{T}) \cdot r_0(\mathrm{cm})$
Quadrupole	$\frac{B' r_0^2}{2\mu_0} \approx 40 \times B'(\mathrm{T/m}) \cdot [r_0(\mathrm{cm})]^2$
Sextupole	$\frac{B'' r_0^3}{6\mu_0} \approx 0.14 \times B''(\mathrm{T/m^2}) \cdot [r_0(\mathrm{cm})]^3$

(Ampere.turns needed in reality will be slightly more due to approximations used)

Choice of Conductor

- For a given strength requirement, the number of ampere.turns is fixed, and may be achieved by any combination of Amps and corresponding number of turns.
- The conductor cross section is determined by the desired operating current and current density that can be achieved.
- For air cooled coils, it is generally safe to stay below 1 A/mm^2.
- Water cooled hollow conductors allow much higher current densities, depending on temperature rise acceptable. (Typical current densities $\leq$10 A/mm^2, typical ΔT $\leq$ 10 C.)
- Indirect cooling (chill plates) may be used when air cooling is marginally insufficient (not very common).

Space needed for coils

- Once a conductor is chosen and the operating current density is determined, the 2-D cross sectional area of the coils is given by the ampere.turns needed: Area of coils (per side) = $(NI)/J$
- The area must be adjusted for the space occupied by insulation on the conductor, gaps between turns and layers, and final insulation thickness.
- The required coil cross sectional area must be provided in the final magnet design in order to meet the strength requirement.
- The size of the magnet, the poles geometry, and the turns distribution are chosen to accommodate the coil while satisfying other constraints (stay clear zones, iron saturation, …)

Pole Profile Design

- The magnet poles must have the basic reflection (left-right and top-bottom) and rotational symmetries demanded by the type of field to be produced (dipole, quadrupole, etc.) [see slides 25-34]
- For an arbitrary pole shape, several harmonics are allowed, even with the symmetries mentioned above. (Example: Dipole symmetry allows n = 1,3,5,…, quadrupole symmetry allows n = 2, 6, 10, …, sextupole symmetry allows n = 3, 9, 15, …)
- The goal of pole profile design is to shape the poles such that only the desired harmonic survives and all the undesired (but allowed) harmonics are minimized as much as possible, while keeping peak fields low and honoring other physical constraints.

Theoretically Ideal Pole Profile

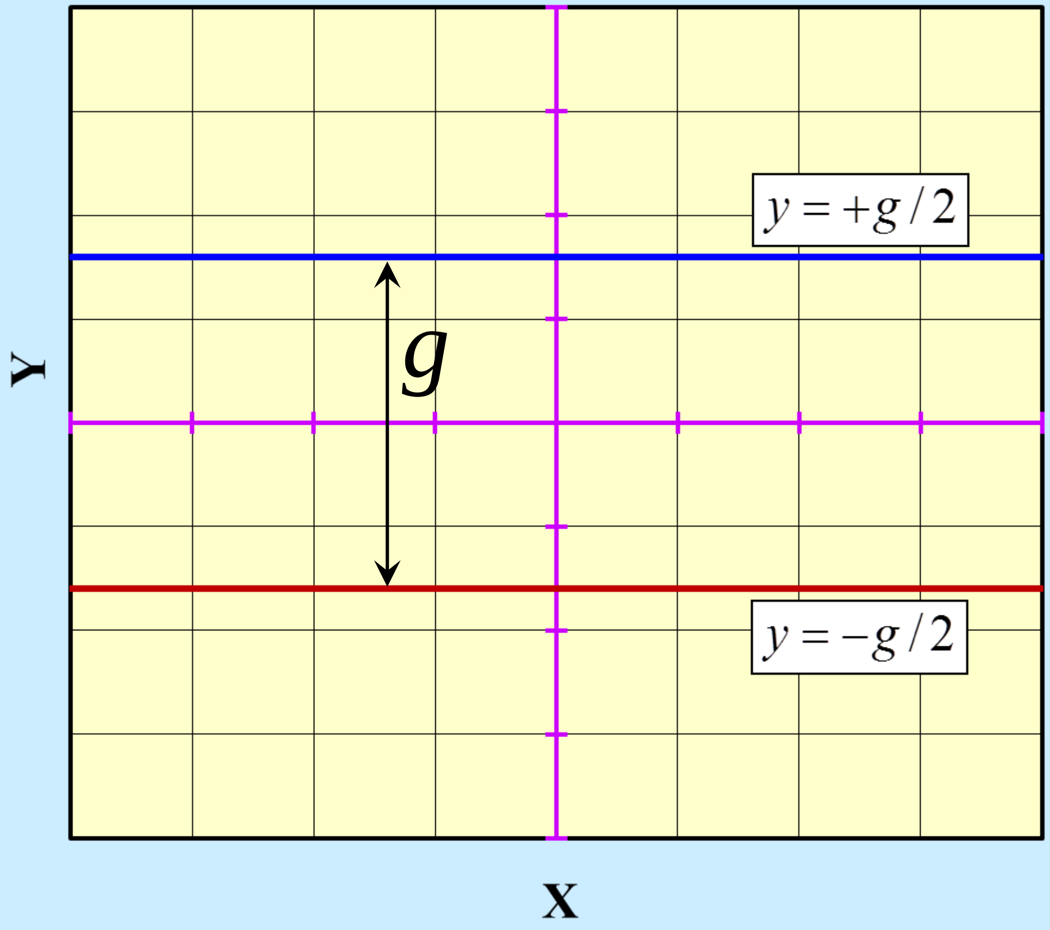
- The shape of field lines for an ideal magnet of a given type (i.e., magnet producing only a single harmonic) is known from solution of Maxwell's equations. (see slides 10-14)
- Field in the aperture is the gradient of a scalar potential, Φ_m, and is therefore normal to equipotential surface. (see slide 7)
- For infinite permeability, field lines are also normal to the iron surface due to boundary conditions. (see slide 43)
- If we shape the iron pole profile to match an equipotential surface for the type of field desired, we should get a pure harmonic field (subject to approximations of infinite permeability)
  $\Rightarrow$ Theoretically ideal pole profile

Ideal Pole Profile for Dipole Field

$$B_y(x,y) = B_0 = \frac{\partial \Phi_m}{\partial y}$$

$$\Phi_m = B_0 y = \text{constant}$$

$$\boxed{\begin{aligned} y &= \text{constant} = \pm g/2 \\ g &= \text{Dipole Gap} \end{aligned}}$$

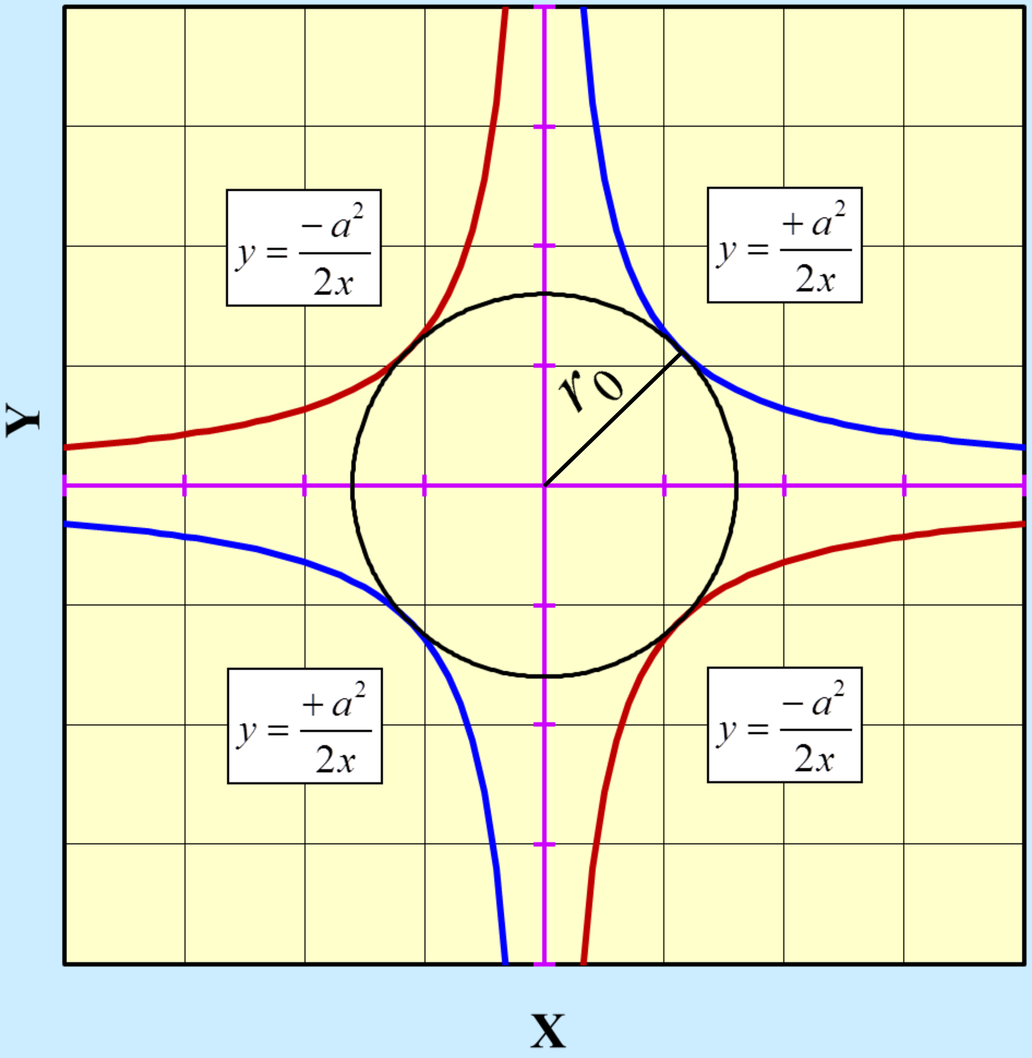


Ideal Pole Profile for Quadrupole Field

$$B_y(x,y) = B'x = \frac{\partial \Phi_m}{\partial y}$$

$$\Phi_m = B'xy = \text{constant}$$

$$\boxed{xy = \text{constant} = \pm \frac{r_0^2}{2}}$$

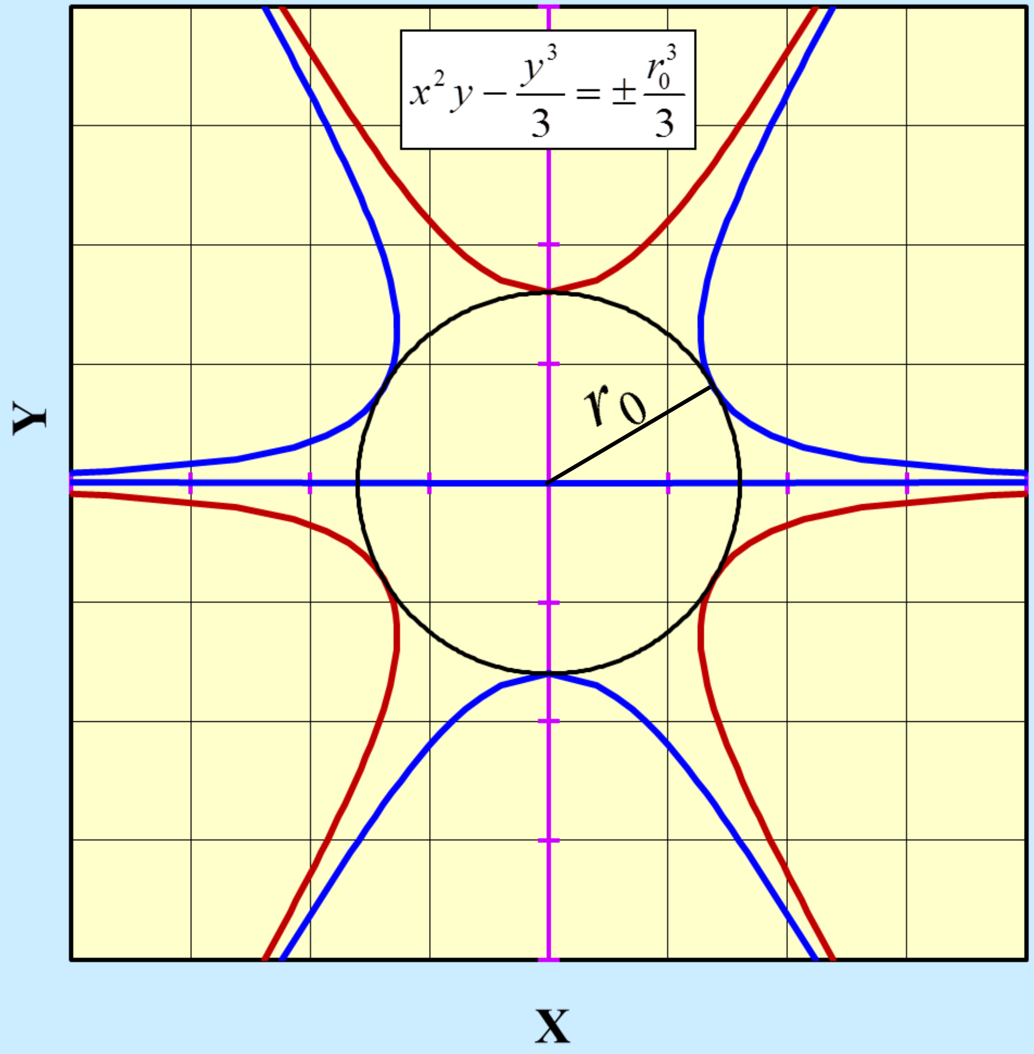


Ideal Pole Profile for Sextupole Field

$$B_y(x,y) = \frac{B''}{2}\left(x^2 - y^2\right) = \frac{\partial \Phi_m}{\partial y}$$

$$\Phi_m = \frac{B''}{2}\left(x^2 y - \frac{y^3}{3}\right) = \text{constant}$$

$$\boxed{\left(x^2 y - \frac{y^3}{3}\right) = \text{constant} = \pm\frac{r_0^3}{3}}$$



What is Wrong with the Ideal Profile?

- Profile extends to infinity and is not strictly realizable.
- No room to accommodate coils for exciting the poles.
- In practice, the poles must be truncated at some suitable width to accommodate the coils.
- The truncation destroys the pure nature of the multipole field, and introduces higher order harmonics, which may be quite large.
- The pole shape must then be reoptimized anyway to minimize the higher order terms which may be at unacceptable levels due to truncation.

Steps Towards Yoke Magnetic Design

- Determine the space needed for the coils (field strength, current density, insulation type).
- Determine the clear bore radius and approximate boundary of the poles such that all required clearances are satisfied and the coil can be accommodated. (Iterative, use judgment)
- Choose backleg dimensions for providing sufficient flux return path and mechanical stability, while still fitting inside any specified envelope. (Iterative, use judgment)
- Compute field harmonics, flux in the iron, etc. and make adjustments if there is too little, or too much iron (saturation).
- Optimize the shape of pole tips to minimize higher harmonics.

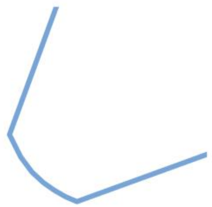
Example: ESRF Quadrupole Optimization

- Parameterize the pole tip profile
  - as deviations from a truncated hyperbola, expressed as a sum of Legendre polynomials (these are smooth functions)
  - allows to express a more complex profile without too many free parameters (as opposed to a profile based on linear segments)
- Define a "cost function" based on computed field quality and a penalty for violating any required clearances.
- Vary the parameters that define the pole tip shape to minimize the "cost function"
- Fast 3-D computations using RADIA software

(Based on *Le Bec, et al., Proc. IPAC2014, June 15-20, 2014, Desden, pp. 1232-4*)

Example: ESRF Quadrupole Pole Optimization

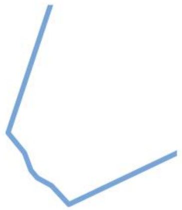
Before optimization



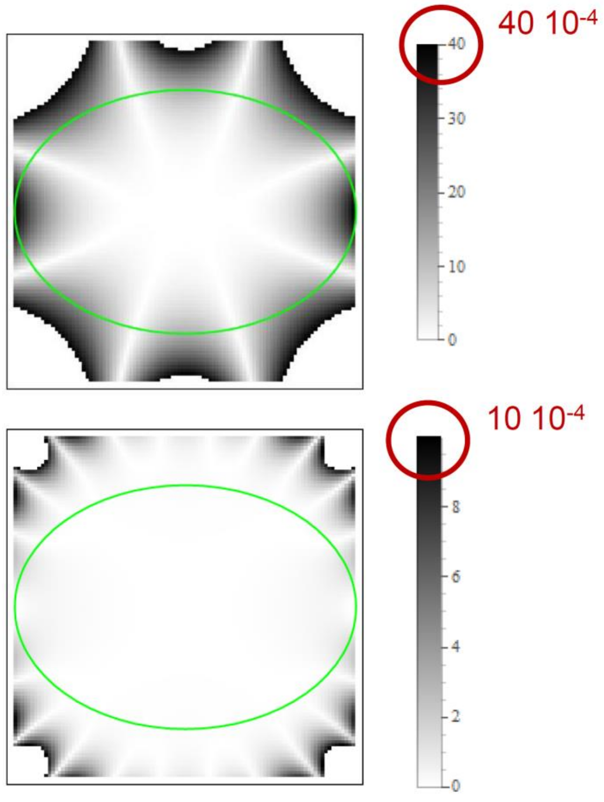
Standard pole profile: truncated hyperbola

After optimization

- Computation time <1h with a 3D model



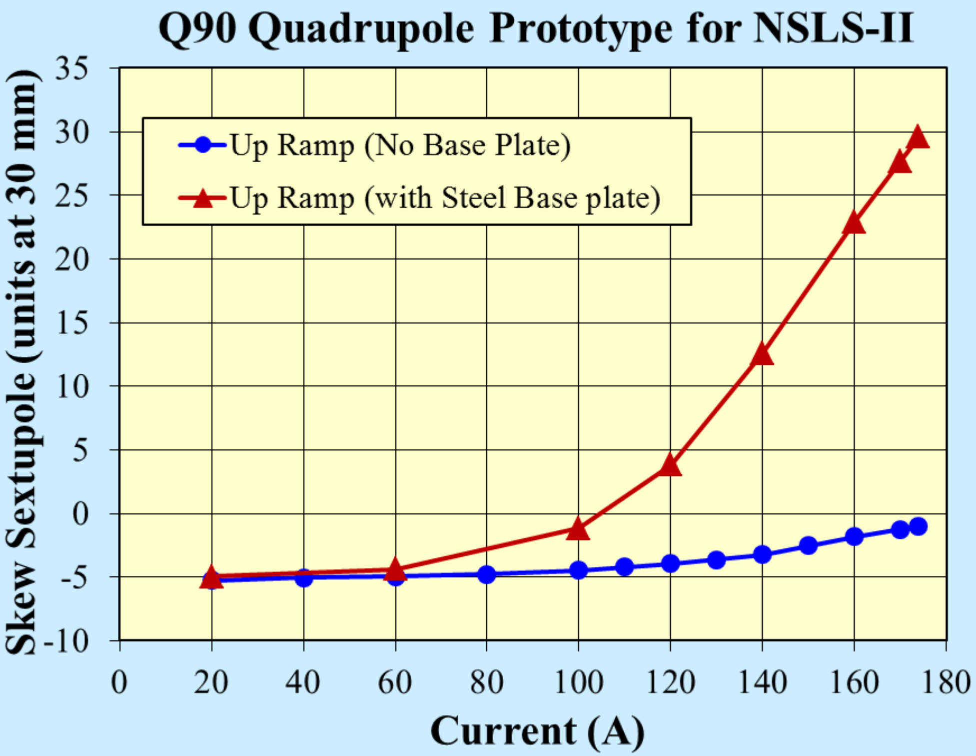
Optimized pole profile



Gradient error plots (1000 $\Delta g/g$). Top: $\Delta g/g$ < 0.4%, before optimization. Bottom: $\Delta g/g$ < 0.1%, after optimization. The field was specified within the green ellipse.

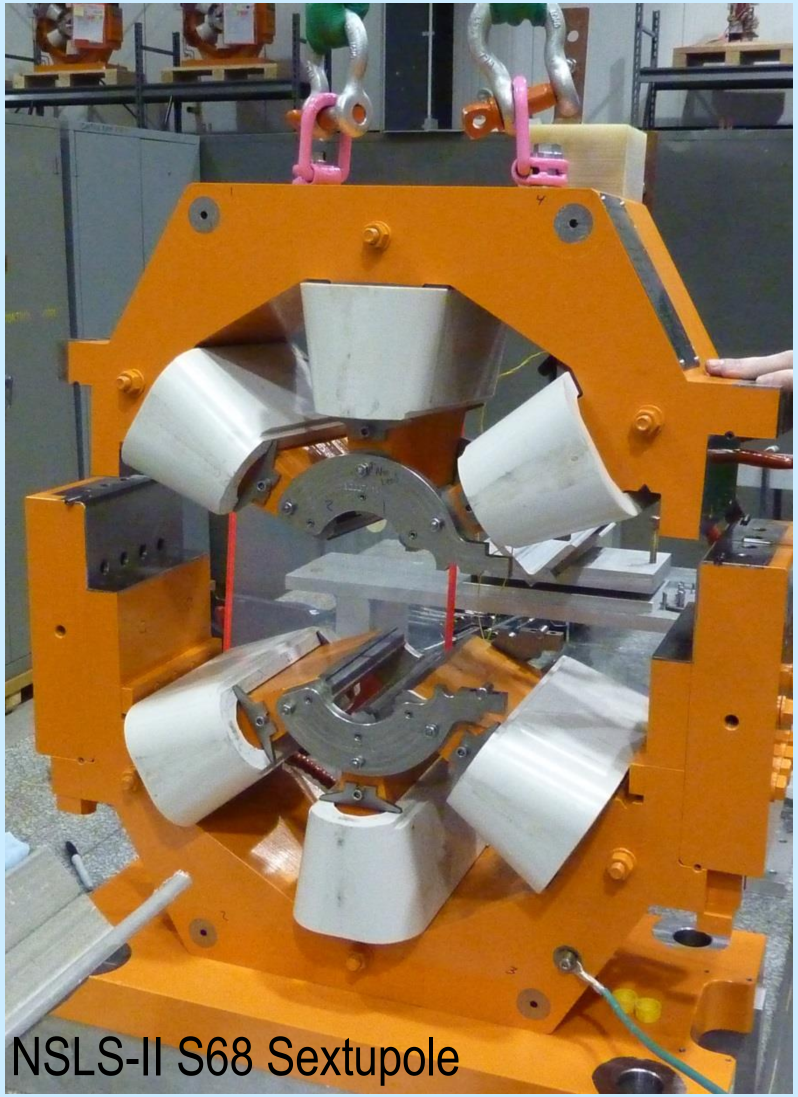
(From *G. Le Bec et al., Low Emittance Rings Workshop, July 8-10, 2013, Oxford.*)

Consequences of Inadequate Iron Yoke



Magnet showed much better field quality when supported on wooden blocks. When mounted on a steel base plate, a top-bottom asymmetry was created due to flux leaking into the base plate, resulting in large skew sextupole.

Mechanically Inadequate Yoke


NSLS-II S68 Sextupole

- Magnets need to be split at least once to install the vacuum chamber.
- Yoke in this case was adequate magnetically.
- Lifting upper half caused a deformation, which in turn caused a displacement of the removable center pole via the pole clamps.
- This resulted in non-reproducibility of skew octupole and normal decapole harmonics (a_4 and b_5).
- Solved by eliminating the pole clamps.
- Harmonics sensitive to bolt torques.

Magnets for Low Emittance Rings

- Upcoming low emittance rings are based on multi-bend acromat (MBA) lattice. The MBA lattice designs impose severe demands on the magnets:
  - Several bending elements within a cell (typically 5 or more)
  - More magnetic elements to fit within a limited space (a hard constraint, particularly for upgrades of existing facilities)
  - Much stronger quadrupoles and sextupoles
  - Longitudinal gradient and high transverse gradient dipoles
  - Tight alignment tolerances (~30 μm RMS magnet to magnet)
  - Magnet design should allow easy installation and alignment to save cost and installation time

Typical Magnet Requirements

Magnet Type	NSLS-II		Max-IV [1]		APS-U [2]	
	Number	Max Value	Number	Max Value	Number	Max Value
Bending Elements (B, B')	60	0.4 T 0 T/m	140	0.524 T 8.62 T/m	280	0.634 T 48.3 T/m
Quadrupoles (B')	300	17.8 T/m	320	40.3 T/m	640	79.9 T/m
Sextupoles (B'')	270	359 T/m2	360	4138 T/m^2	240	5332 T/m^2
Octupoles (B''')	0	--	120	1.95×10^5 T/m^3	0	--
X-Y Correctors ($\Delta\theta$)[3]	180	0.82 mr	200	0.25 mr	See Note (4)	0.30 mr
Total Magnets	810		1140		1160	
Circumference	792 m		528 m		1104 m	
Beam Energy	3 GeV		3 GeV		6 GeV	

(1) Based on M. Johansson, et al., *J. Synchrotron Rad. 21, 884-903 (2014)*

(2) Based on APS-U Ver. 3 lattice (March 2014)

(3) Horizontal and vertical correctors are counted as a single unit, although they are separated in Max-IV.

(4) Ver. 3 lattice assumed correctors in every quadrupole and sextupole, but it is being reconsidered.

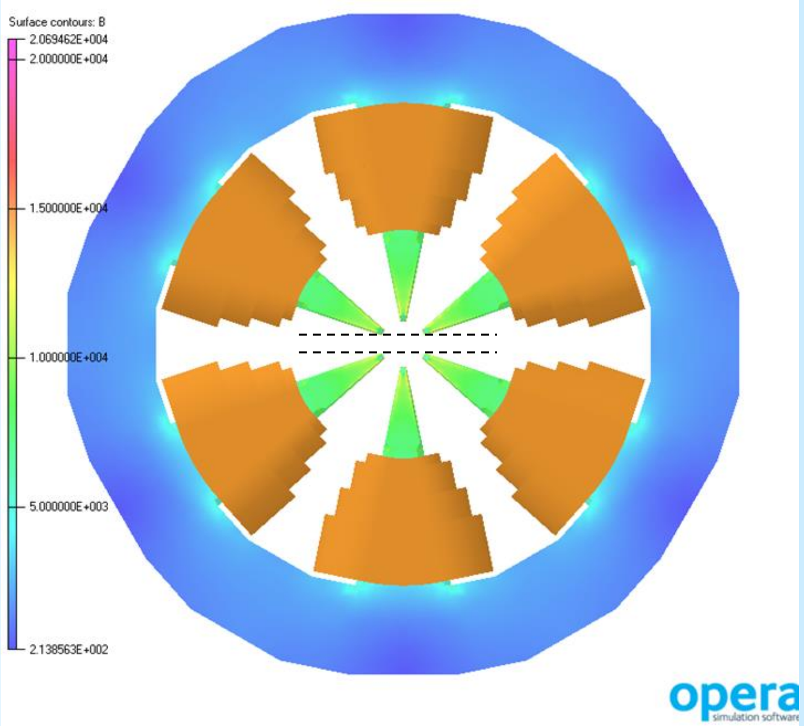
Achieving High Field Strengths

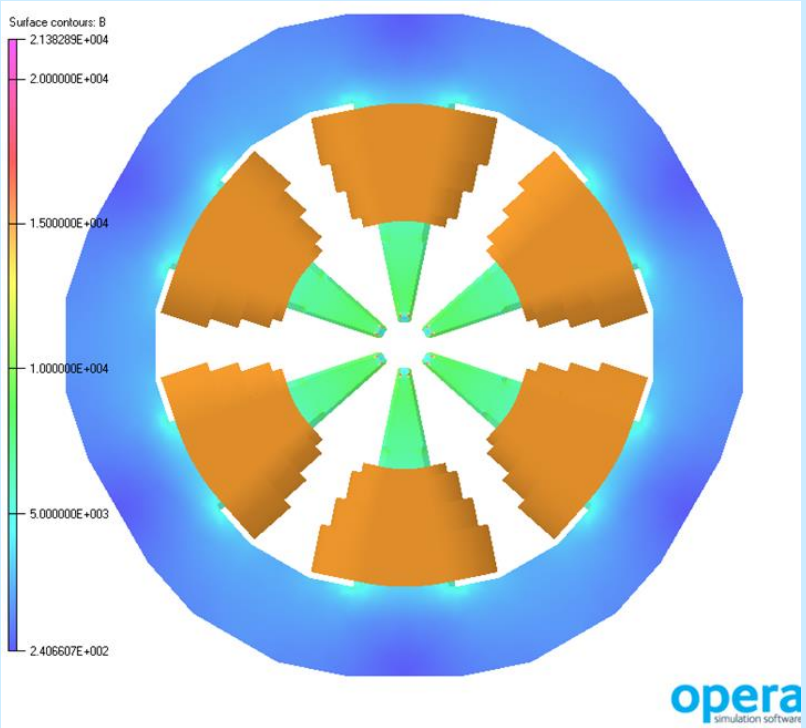
- Field achievable in conventional magnets is limited primarily by the current density and peak field in the iron yoke:
  - Iron Saturation $\Rightarrow$ Low efficiency, non-linearity, field quality issues
- Obvious solution is to reduce the magnet aperture (r_0):
  - Pole tip field in a $2n$-pole magnet $\propto$ r_0^{n-1} (less saturation)
  - Ampere.turns needed in a $2n$-pole magnet $\propto$ r_0^n (smaller coils)
- Smaller aperture also allows magnets to be placed closer together without introducing significant cross-talk (faster fringe field fall-off).
- There are limitations on how small the aperture can be made, which lead to challenges in meeting all the magnet requirements.

Factors Limiting Aperture Reduction

- Need to accommodate a vacuum chamber of size sufficient to achieve good vacuum.
  - Typically ~25 mm magnet aperture for upcoming storage rings
- Need to provide clearances for other items, e.g. vacuum chamber cooling lines, photon extraction, etc.
  - APS-U: pole-to-pole ≥ 10 mm; coil-to-coil ≥ 10-16 mm
- Need to accommodate a coil of size sufficient to achieve the required Ampere.turns with reasonable current density
  - Higher current densities ⇒ water cooled conductor ("bulky")
- Need to provide good field quality within a specified radius (typically ~ 7-10 mm radius for upcoming machines).

Example: Limitation Due to Constraints





(Courtesy *Mark Jaski, APS Upgrade, Argonne*)

13 mm aperture radius
10 mm vertical gap between pole tips
18-pole = -735 units at 10 mm

13 mm aperture radius
6.7 mm vertical gap between pole tips
18-pole = +73 units at 10 mm
10% more field for the same saturation

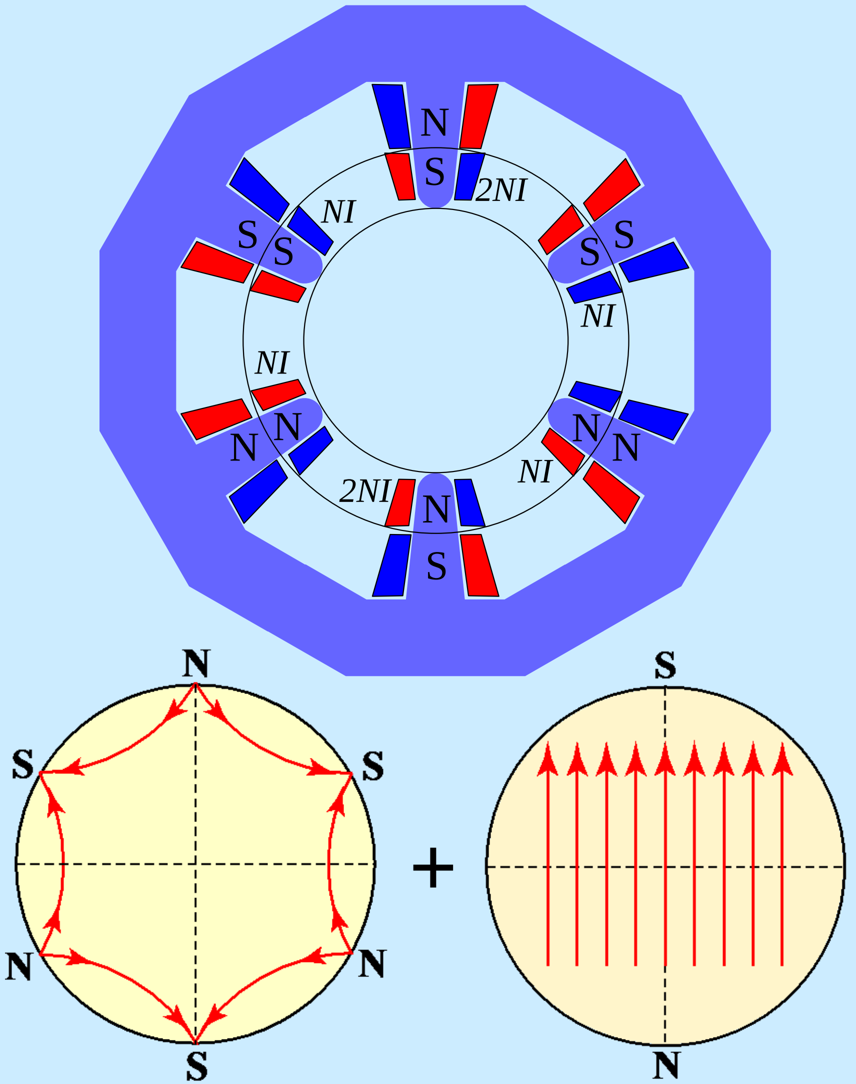
Minimizing Space Needed

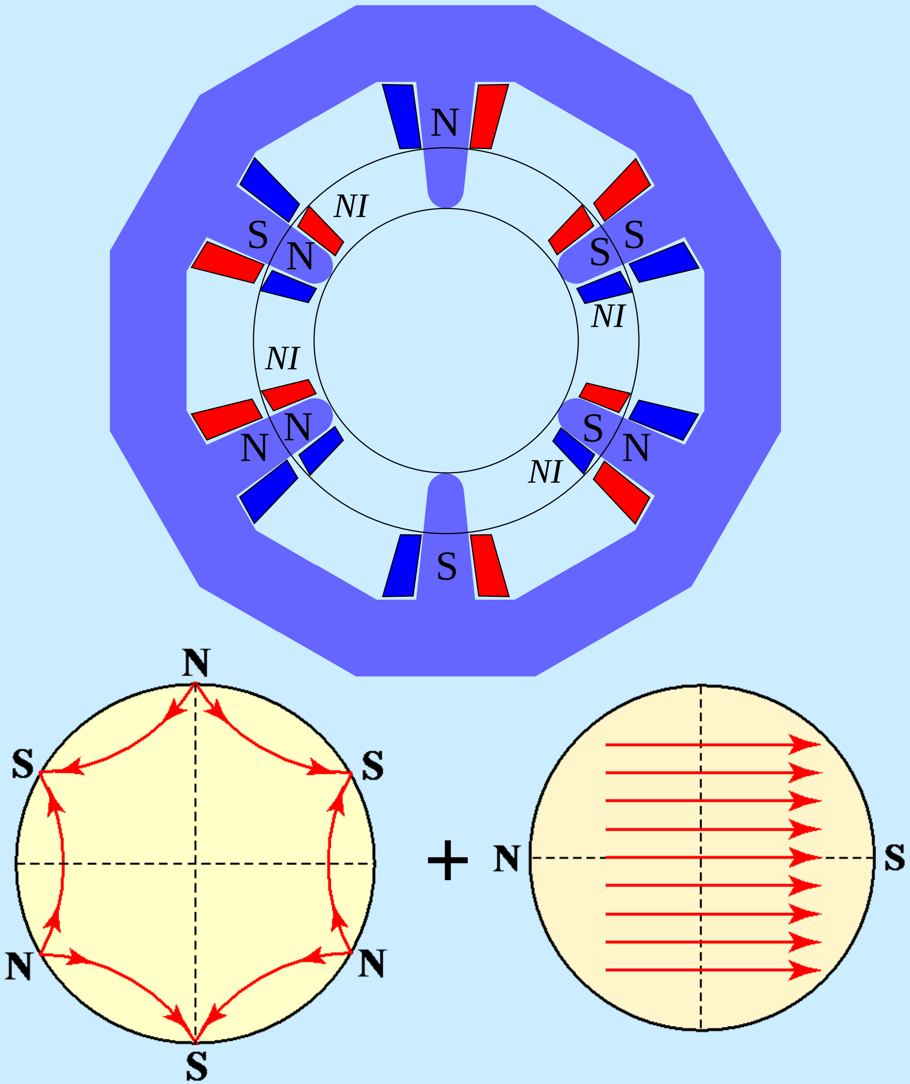
- Typically, integrated strength is of primary interest
  - Integrated Strength = Central Strength x Magnetic Length
- Drive the central field strength as high as possible, limited by *reasonable* saturation of the iron yoke, to minimize length.
- Compact coil ends to maximize iron yoke length, within a given available space (smallest useable conductor, more turns/layer).
- Integrated correctors built into quadrupoles and sextupoles
  - No extra longitudinal space consumed by correctors
  - Horizontal and vertical steering dipoles in quadrupoles
  - Steering dipoles and skew quadrupole in sextupoles
  - **But there are drawbacks too!**

Integrated Dipole Correctors

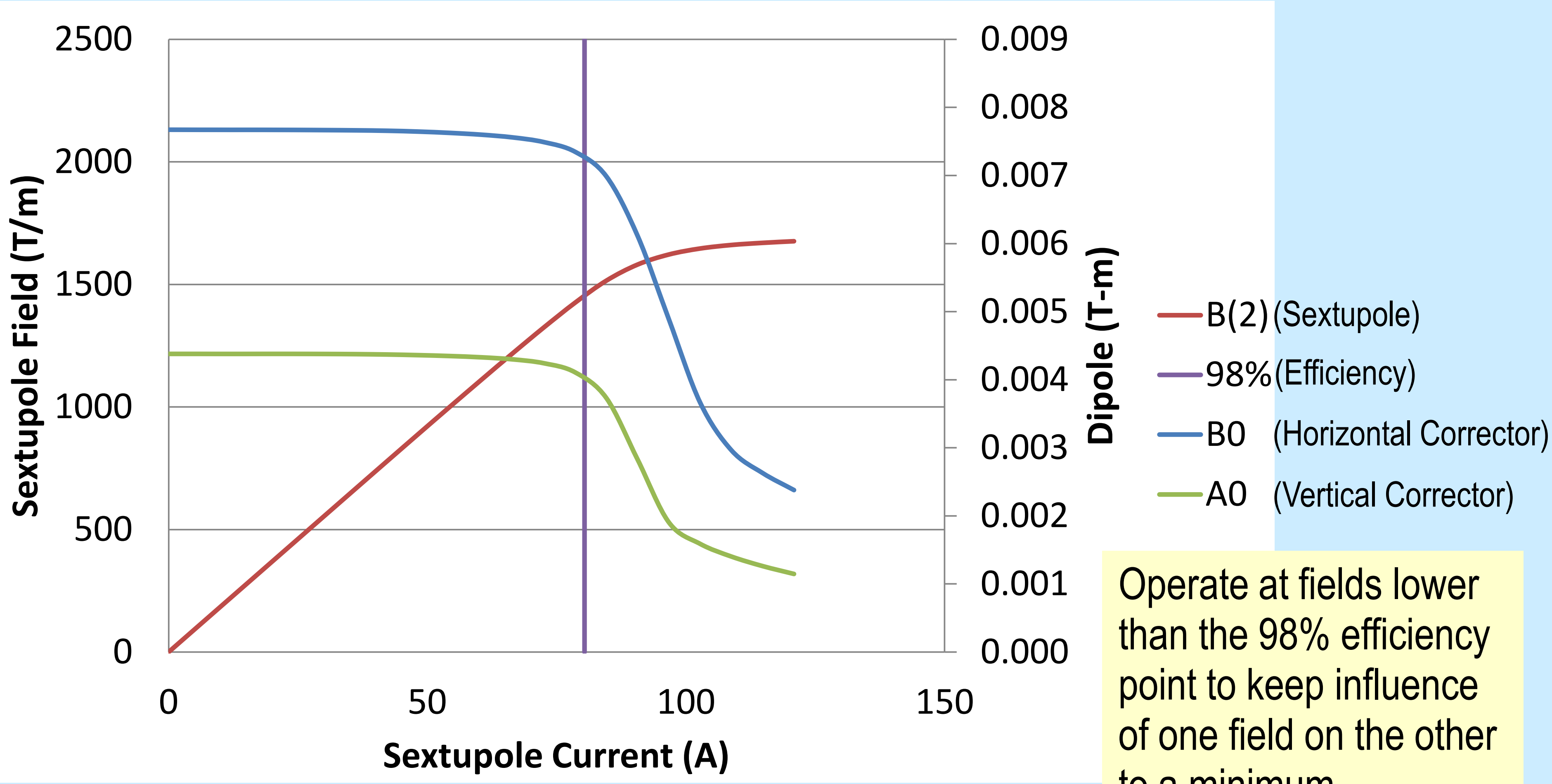
- Quadrupole and sextupole pole geometries are not optimized to produce a pure dipole field
  - Dipoles in a quadrupole produce large sextupole and decapole
  - Dipole correctors in sextupoles may be designed to produce zero sextupole, but the decapole term is still large.
  - Skew quadrupole correctors in sextupoles produce large amounts of skew octupole, which may be unacceptable
- If the iron yoke is saturated, excitation of the correctors influences the strength of the main field, and vice versa
  - Prevents driving central field too high (counter productive!)
  - Makes operation complicated (need look up tables to set currents)
  - Main field may depend on the corrector excitation *history*

Dipole Correctors in a Sextupole





Dipole Strength Vs. Sextupole Setting



Operate at fields lower than the 98% efficiency point to keep influence of one field on the other to a minimum.

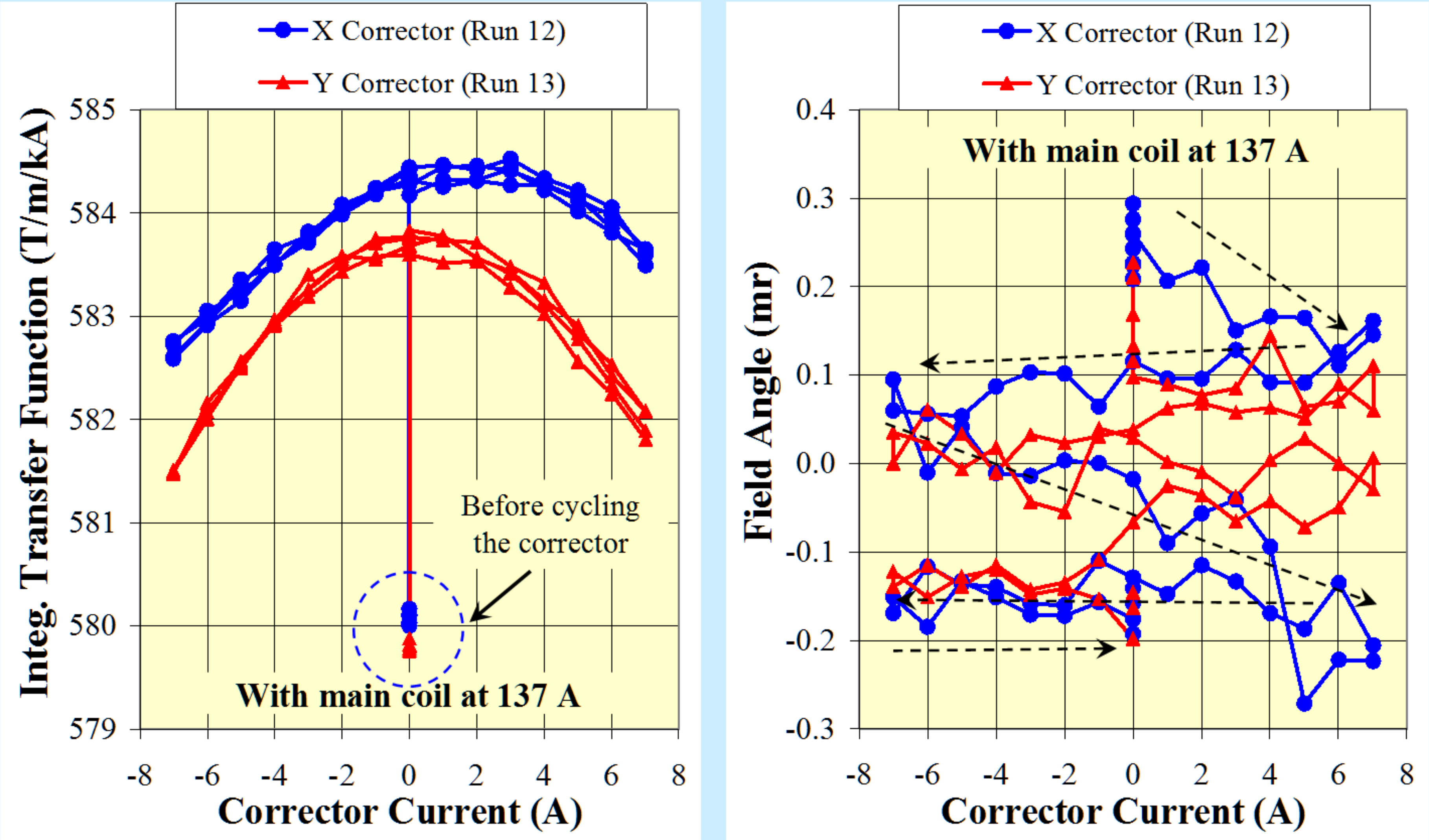
(Courtesy *Mark Jaski, APS Upgrade, Argonne*)

Measurements in a SLS Sextupole

- Main coil was first cycled three times between 0 A and 140 A, with the trim coils unpowered, to set the iron history to a known state with 6-fold symmetery. The main coil was then ramped up to 140 A.
- Five readings were taken with the trim coils unpowered.
- One of the two correctors was cycled five times between –7 A and +7 A to stabilize the iron hysteresis behavior.
- Five readings were then taken again with corrector at 0 A to see the effect of simply changing the magnet history.
- Measurements were then made for various excitations of the corrector coil from –7 A to +7 A in 1 A steps, for both the UP ramp and the DOWN ramp.
- Measurements were repeated for another full cycle of the corrector coil excitation.

Sextupole Field Variation with Corrector Strength in SLS Sextupole SRW37

Measurements at BNL with magnet located at axial center of a 2 m long rotating coil.
Absolute values are not related to any magnet fiducial; Only variations are meaningful.



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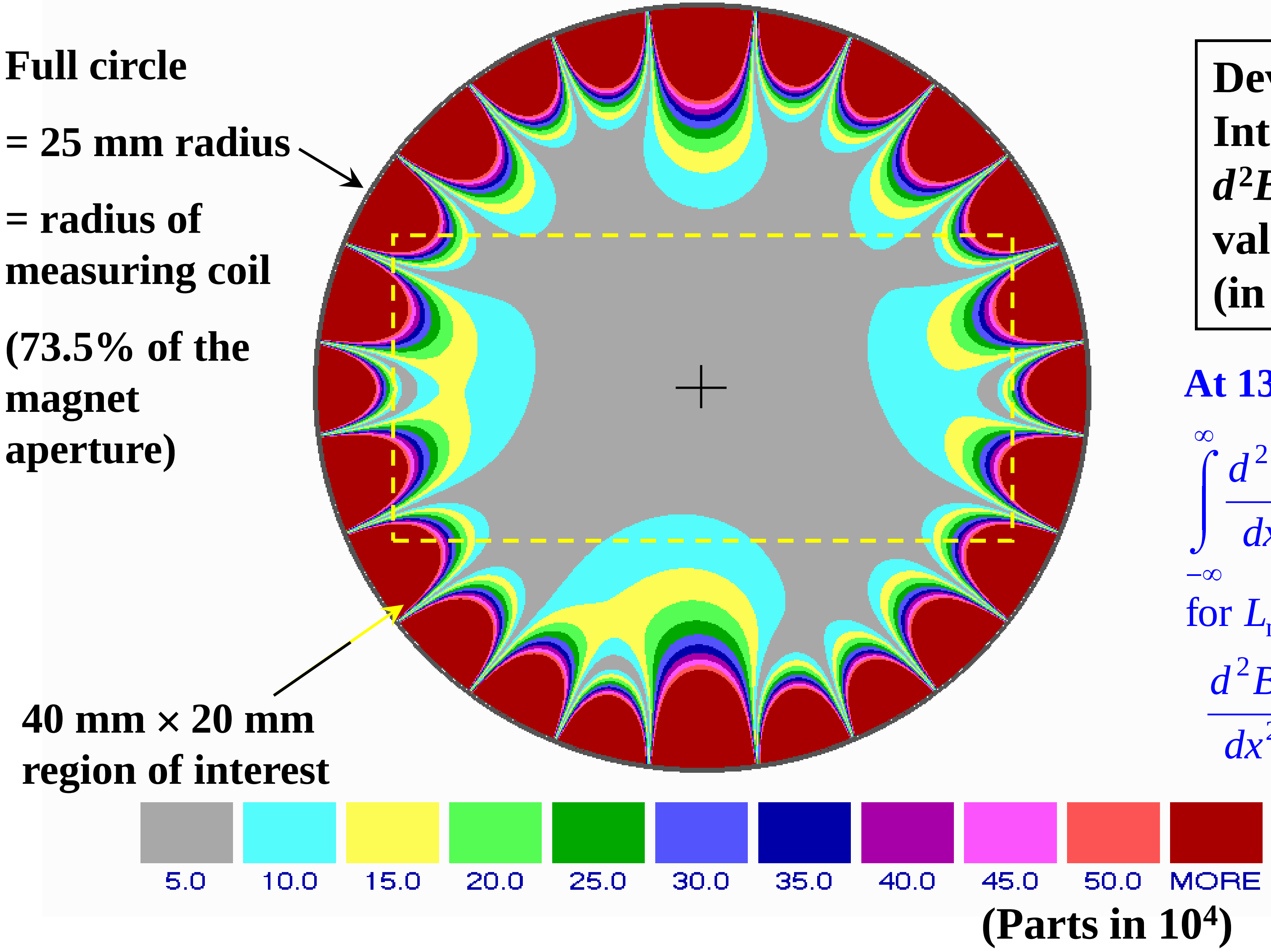
SLS WIDE SEXTUPOLE SRW37(NSLS01); 138 A HARMONICS (RUN 9)



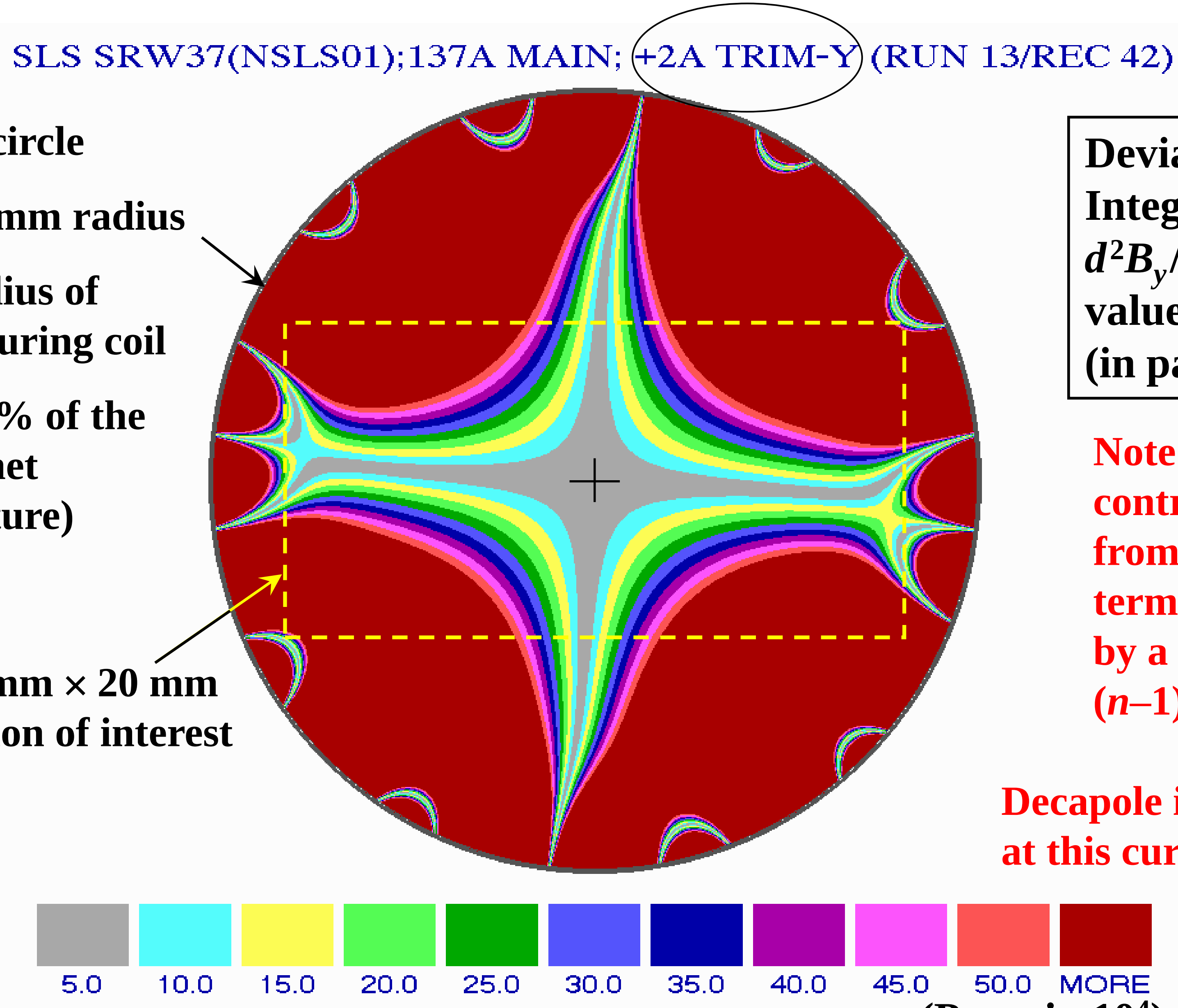
Deviation of Integrated d^2B_y/dx^2 from value on axis (in parts in 10^4)

At 138.3 A; in Center:

$$\int_{-\infty}^{\infty} \frac{d^2B_y}{dx^2}\,dz = 160\ \mathrm{T/m}$$

for $L_{mag} = 0.217$ m,

$$\frac{d^2B_y}{dx^2} = 740\ \mathrm{T/m^2}$$



Full circle

= 25 mm radius

= radius of measuring coil

(73.5% of the magnet aperture)

40 mm × 20 mm region of interest

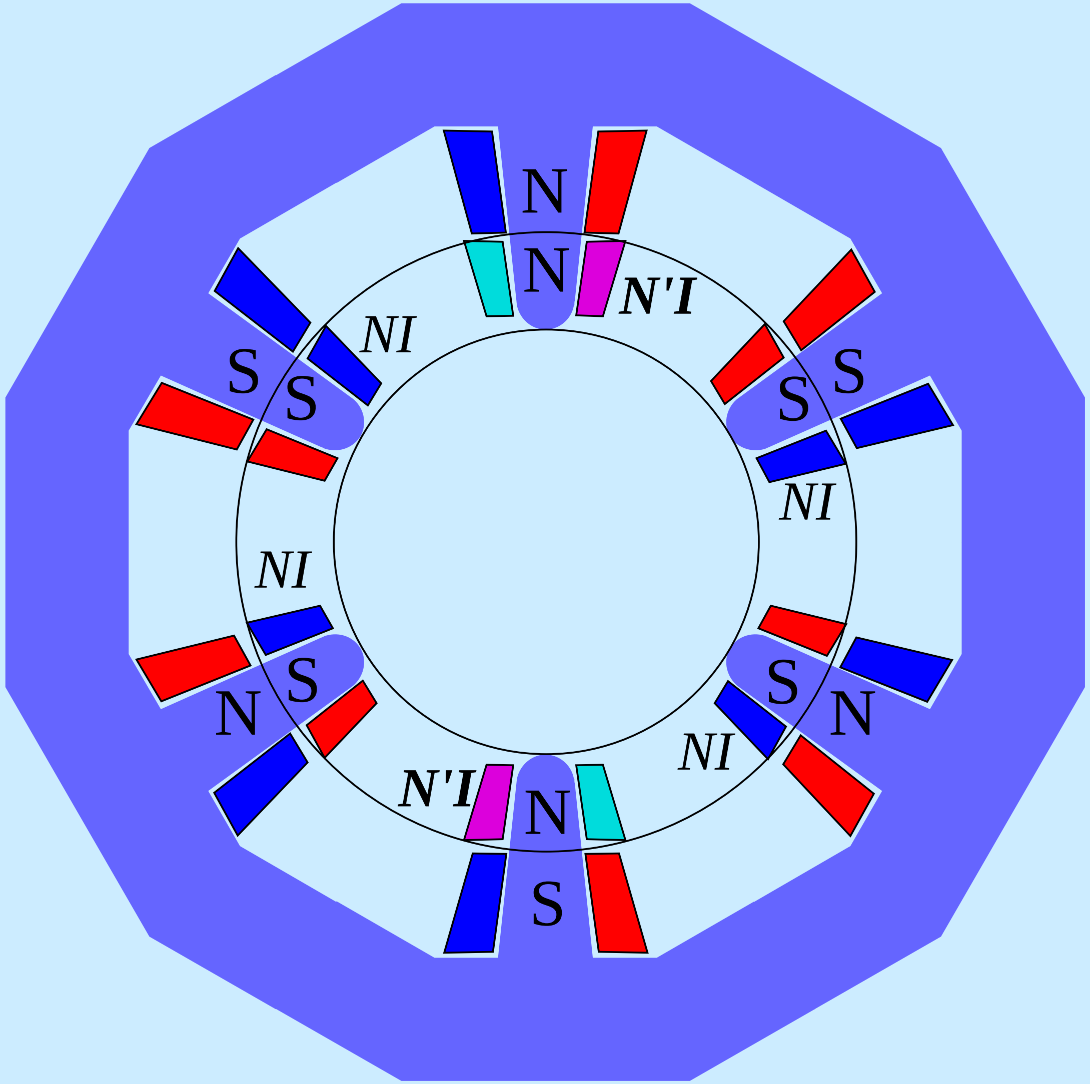
Deviation of Integrated d^2B_y/dx^2 from value on axis (in parts in 10^4)

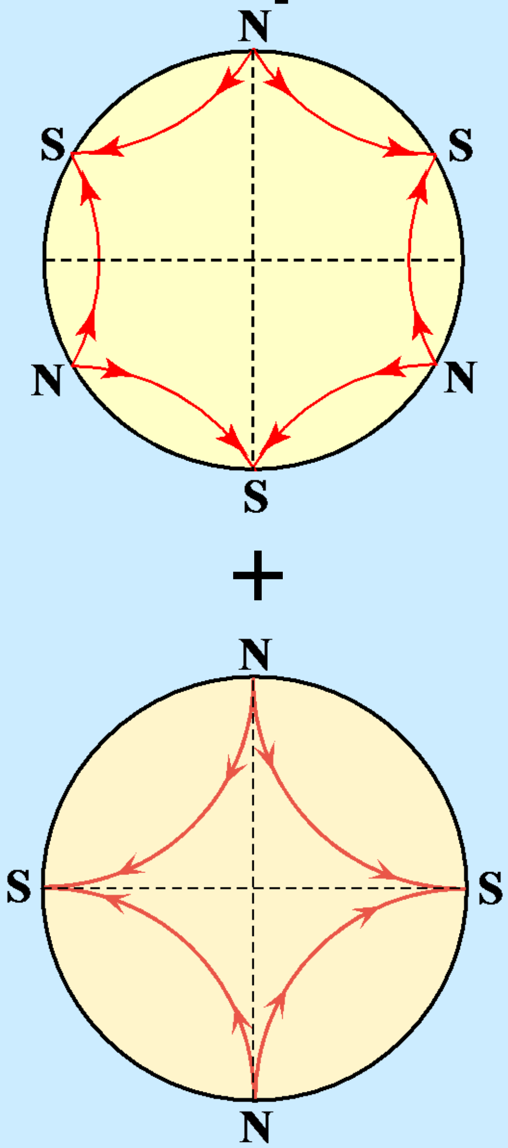
Note that contribution from the 2*n*-pole term is enhanced by a factor of (*n*–1)(*n*–2).

Decapole is –52 units at this current setting.

(Parts in 10^4)

Skew Quad Corrector in a Sextupole





Integrated Correctors Summary

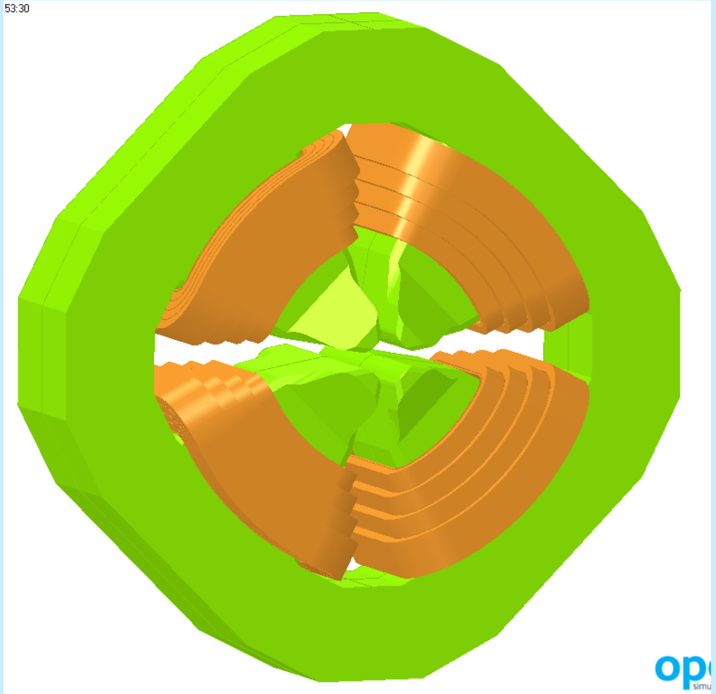
- Integrated correctors are attractive because they save valuable space, and can provide plenty of correction strength.
- The main drawback is the significant impact on field quality.
- These correctors also limit the amount of saturation in the iron yoke that can be tolerated, thus restricting the central field of the main magnet.
- Stand alone correctors are preferable when field quality must be preserved. Many designs exist for such correctors.
- It may be possible to create room for stand alone correctors by driving the main magnets deeper into saturation, thus making them shorter while achieving the same integrated field.

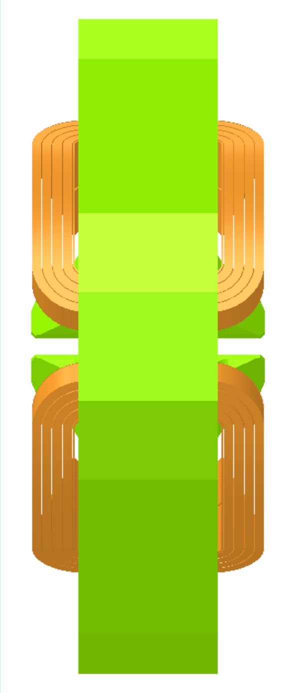
Maximizing the Central Field

- The achievable central field is limited primarily by saturation of the iron yoke.
- Iron saturation causes inefficient utilization of the Ampere.turns, leading to rapidly increasing power dissipation as central field is increased. The temperature rise of cooling water may then become the limiting factor.
- The magnet yoke design should minimize iron saturation by providing adequate iron to the extent possible.
- If the required field can not be achieved with reasonable iron saturation, one option may be to use higher permeability materials, such as Vanadium-permendur for pole tips (**cost?**)

Maximizing the *Magnetic* Length

- The magnet *physical* size must fit within the allocated longitudinal space. This includes the coil ends.
- The *magnetic* length can be increased without increasing the physical size by using pole tip extensions in the ends.





150 mm yoke length

30 mm extension
("Mushroom" ends,
aka "Nose pieces")

(Courtesy *Mark Jaski*,
APS Upgrade, *Argonne*)

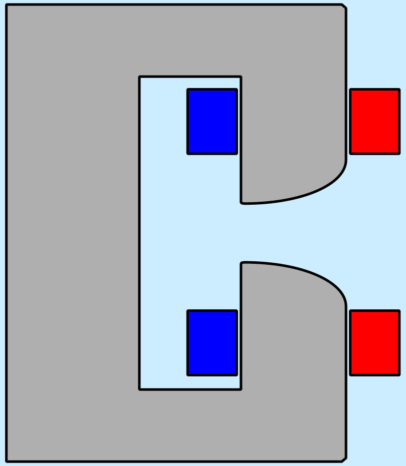
Results with Pole Tip Extension

Parameter	No extension (steel poles)	30 mm extension (each end)
Insertion Length	0.2 m	0.2 m
Efficiency	80%	80%
Current	264.3 A	200.0 A
Central Gradient	87.9 T/m	71.2 T/m
Integrated Gradient	13.26 T	13.76 T
Magnetic Length	**0.151 m**	**0.193 m**
Power Consumed	3588 W	2057 W

(Compiled from data provided by *Mark Jaski*, *APS Upgrade*, *Argonne*)

Transverse Gradient Dipoles

- MBA designs for all upcoming storage rings contain transverse gradient dipoles (combined dipole and quadrupole fields).
- In a conventional approach, the quadrupole field is generated by varying the gap along the transverse (horizontal) direction. This approach would work when the gradient is not too large.
  - Max-IV: $B = 0.524$ T, $B' = 8.62$ T/m, $\Delta B/B = 16.5\%$ over 10 mm

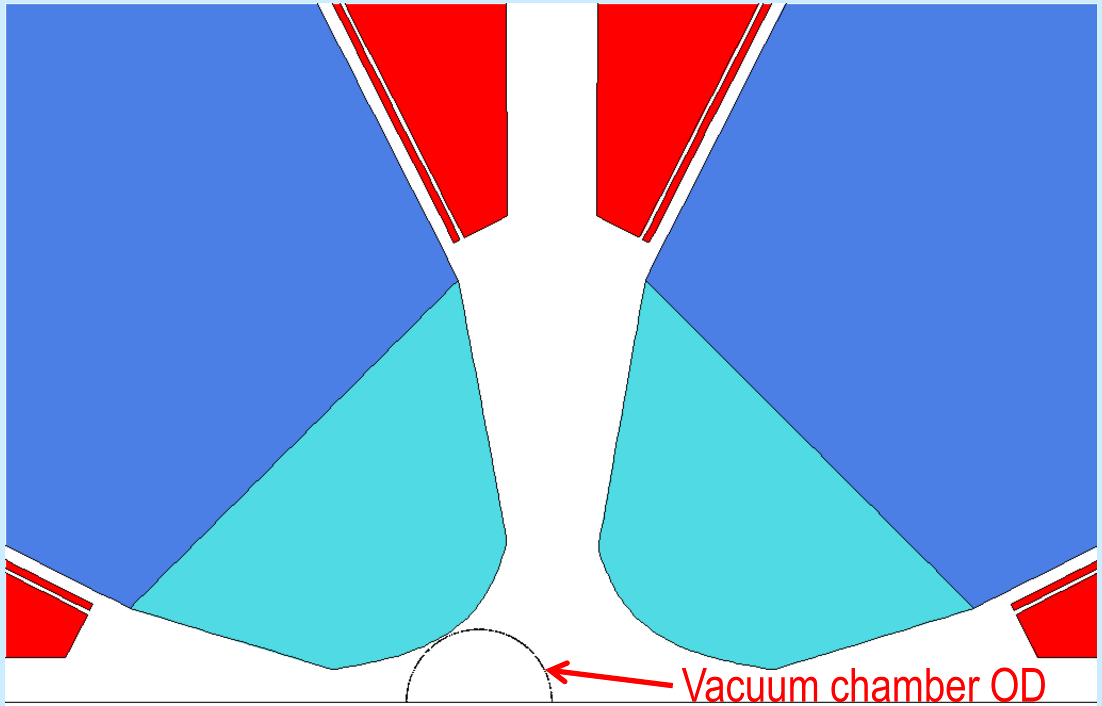


  - Tapered pole profile to obtain the desired gradient.
  - Pole profile is optimized to minimize higher order harmonics.
  - Pole face strips to adjust $B' \pm 4\%$

High Transverse Gradient Dipoles

- The conventional approach of combined function dipoles is not suitable for very high transverse gradients
  - ESRF-U: B = 0.54 T, B' = 34 T/m, $\Delta B/B$ = 63% over 10 mm
  - APS-U: B = 0.535 T, B' = 45.1 T/m, $\Delta B/B$ = 84.3% over 10 mm
    and B = 0.605 T, B' = 48.3 T/m, $\Delta B/B$ = 79.8% over 10 mm
- Such magnets are better viewed as offset quadrupoles:
  - ESRF-U: offset = 15.9 mm from quadrupole center
  - APS-U: offset = 11.86 mm from quadrupole center (M3)
    and offset = 12.53 mm from quadrupole center (M4)
- Need larger aperture, which makes high B' challenging.

High Transverse Gradient Dipoles–APSU

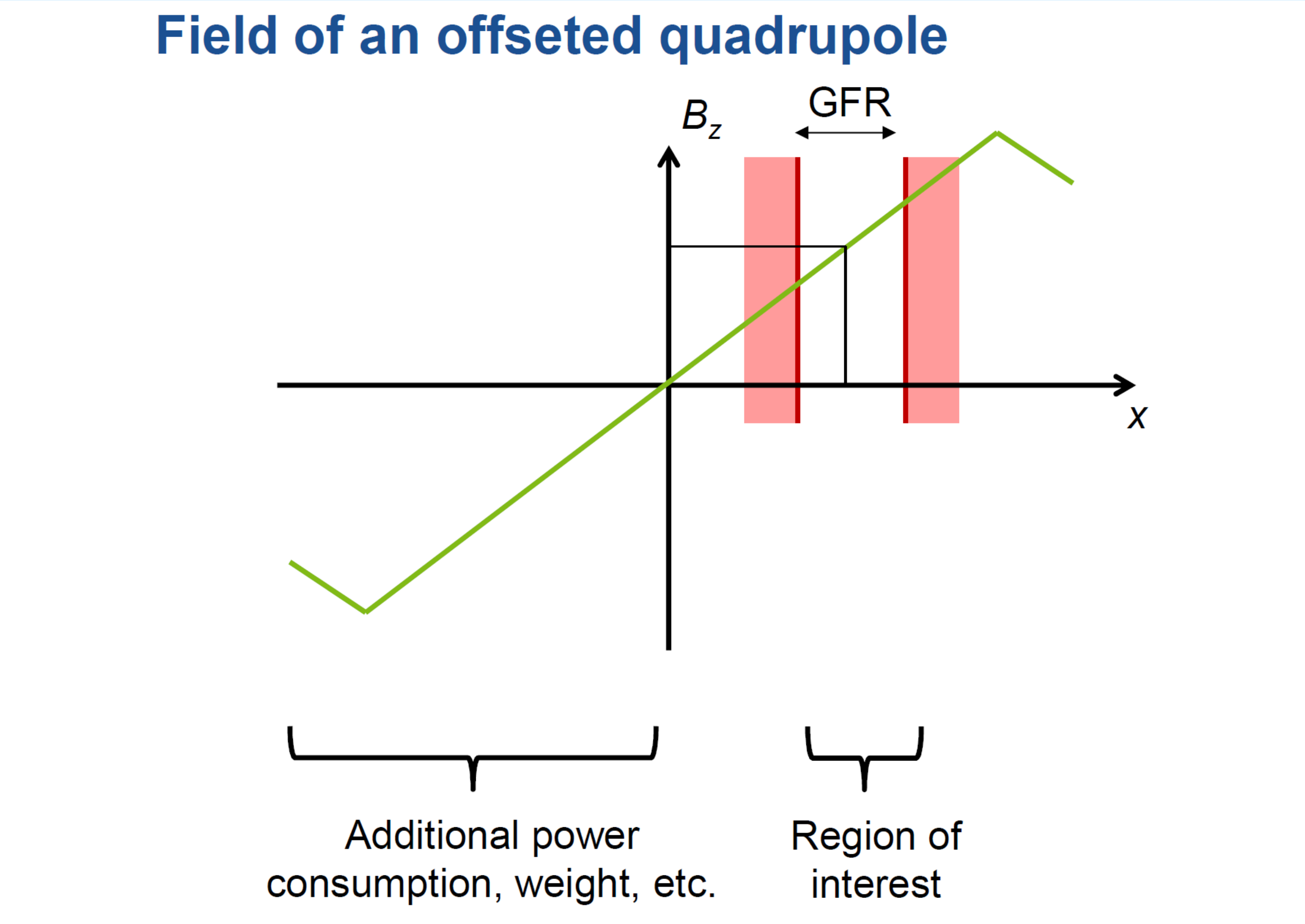


M4 Magnet 19.7 mm aperture radius

(Courtesy *Mark Jaski, APS Upgrade, Argonne*)

- Vanadium-permendur pole tips for improved efficiency.
- Dipole correction coils to allow ±5% adjustment of *B′* keeping a constant *B*.
- Field quality improved by allowing left and right halves to be different.
- Curved pole tips to follow the electron beam trajectory (1.13 deg. bend)

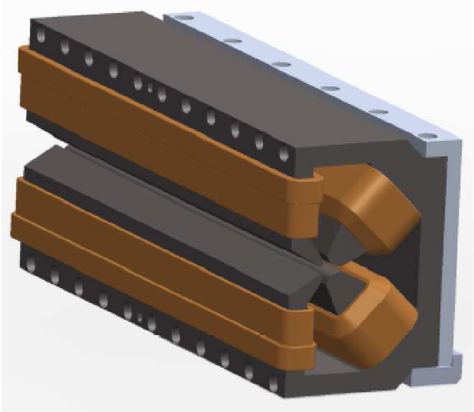
High Transverse Gradient Dipoles–ESRF

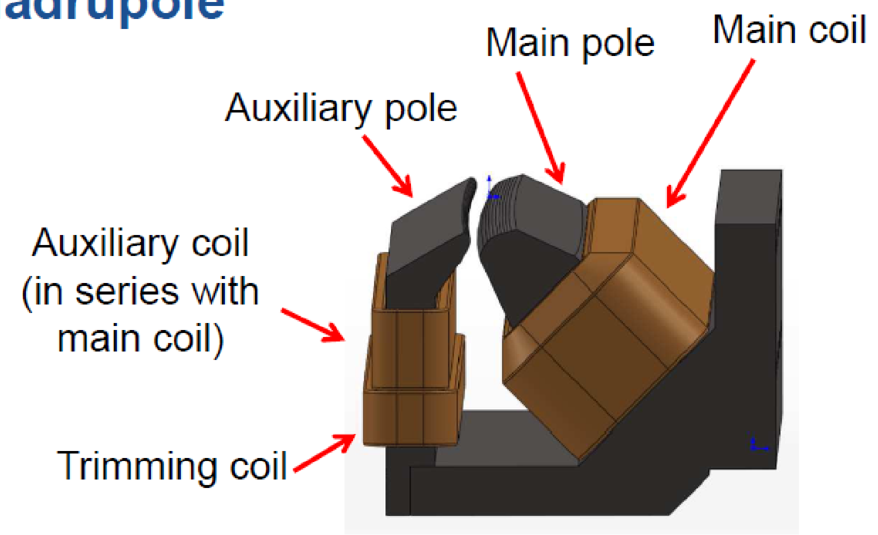


(From *G. Le Bec et al., Low Emittance Rings Workshop, Sept.17-19, 2014, Frascati.*)

High Transverse Gradient Dipoles-ESRF

Single sided dipole – quadrupole



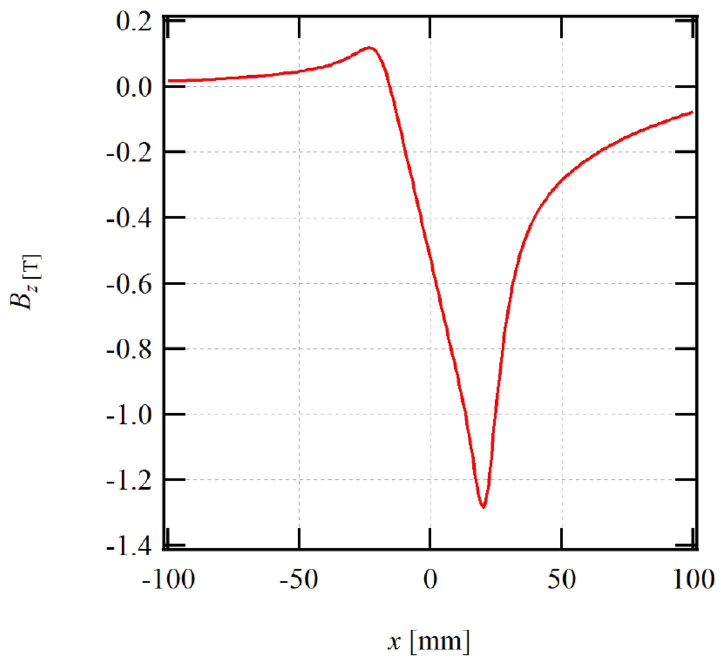


- A "3-pole" design (2 poles + 2 "half" poles)
- 0.54 T field, 34 T/m gradient
- Iron length: 1.1 m
- Magnet mass ~ 1 ton
- Power consumption: 1.7 kW

- **Field is nearly zero outside the magnet.**
- **Easy access on one side**
- **± 2% adjustment in gradient**

From *G. Le Bec and J. Chavanne*
Low Emittance Rings Workshop, Sept.17-19, 2014, Frascati

High Transverse Gradient Dipoles-ESRF



Vertical field vs. position.
Field is almost zero on one side.

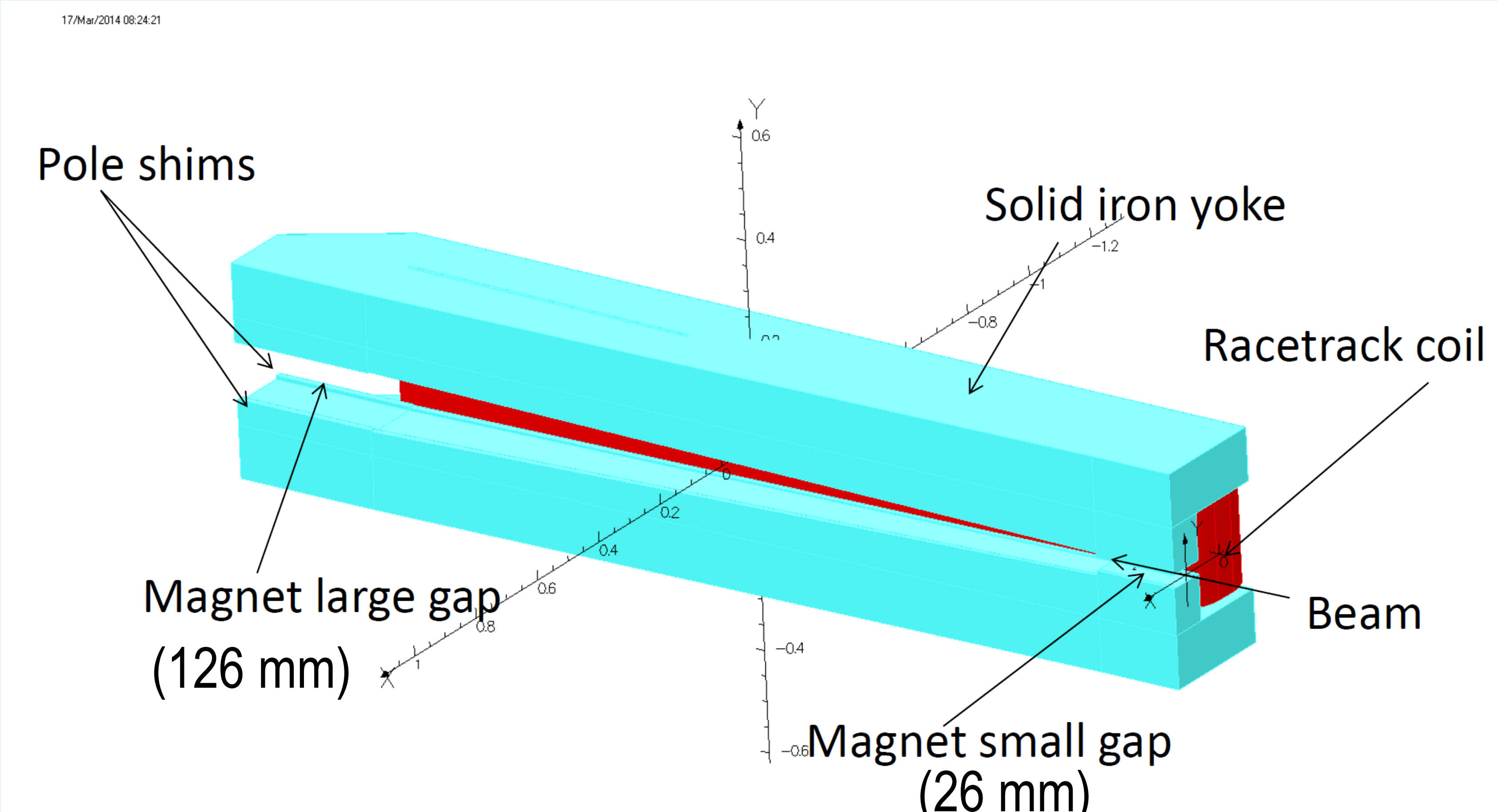
$\Delta G/G$ expressed in 10^{-3}.
Specification: $\Delta G/G < 10^{-2}$.
GFR: 7x5 mm
Field integration along an arc.

From *G. Le Bec and J. Chavanne*
Low Emittance Rings Workshop, Sept.17-19, 2014, Frascati

Longitudinal Gradient Dipoles

- Another type of magnet being used in upcoming low emittance storage ring designs is the longitudinal gradient dipole (L-bend).
- The vertical field in these dipoles varies along the beam path from a high value at one end to a low value at the other end.
- Use of these magnets makes it possible to further reduce the emittance without increasing the number of dipoles.
  - J. Guo, T. Raubenheimer, Proc. EPAC2002, Paris, 1136-8.
- The ratio of the highest and the lowest fields required is ~2-5, but may be as high as ~7. There are two basic approaches:
  - Vary the gap, keeping the coil Ampere.turns the same
  - Vary the Ampere.turns, keeping the gap same

L-Bend Dipoles: Varying Gap



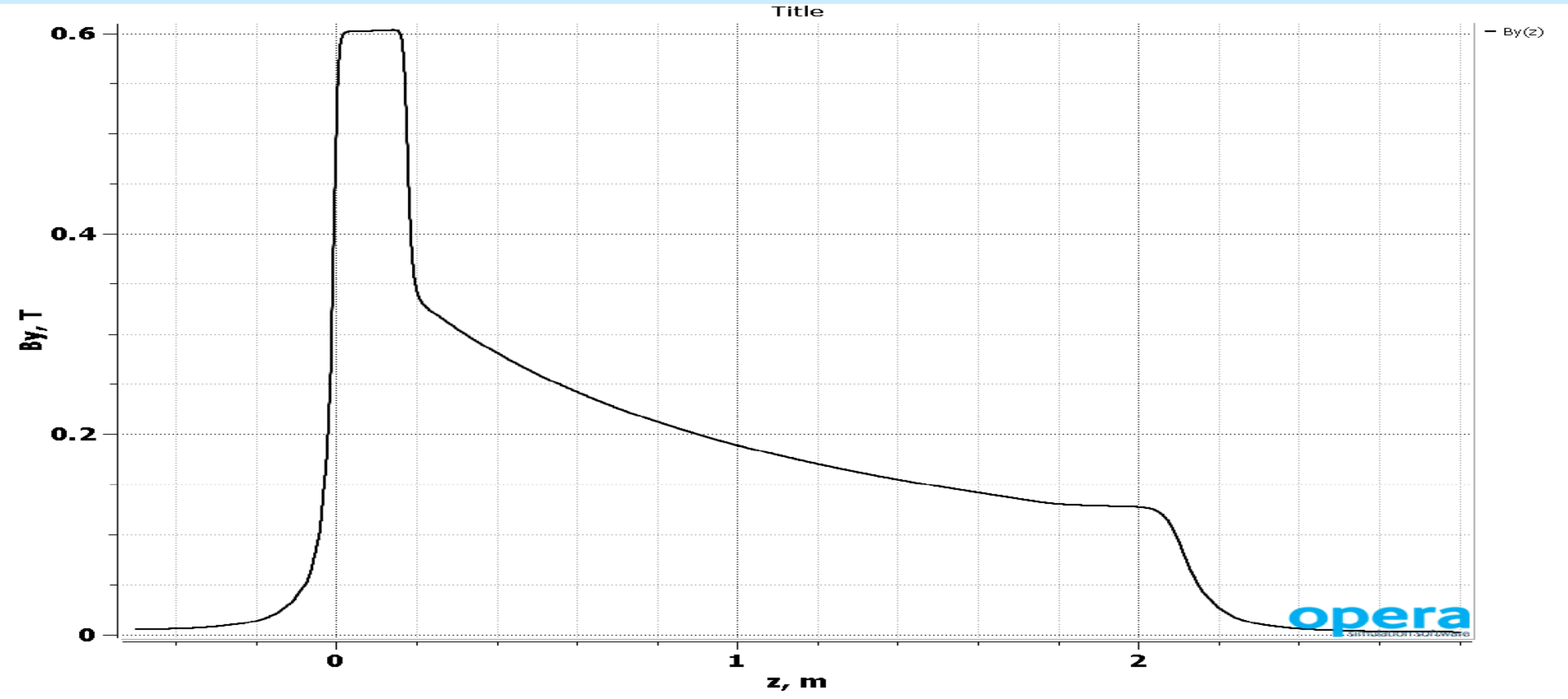
(Courtesy *Vladimir Kashikhin, Fermilab*)

Prototype L-bend for APS Upgrade (B_{max}/B_{min} = 0.634 T/ 0.131 T = 4.84)

L-Bend Dipoles: Varying Gap

- Coil design is simple.
- Provides a smooth variation of field strength with longitudinal position, which avoids field distortions at the transitions.
- But there are drawbacks:
  - The pole width must be increased as the gap increases in order to preserve field quality, even though the required good field region may be small.
  - Magnetic energy is stored in a much larger volume than necessary.
  - More attractive for relatively smaller ratio of maximum to minimum field strengths. (APS-U prototype L-bend is perhaps at the limit).

L-Bend Field Profile: Varying Gap

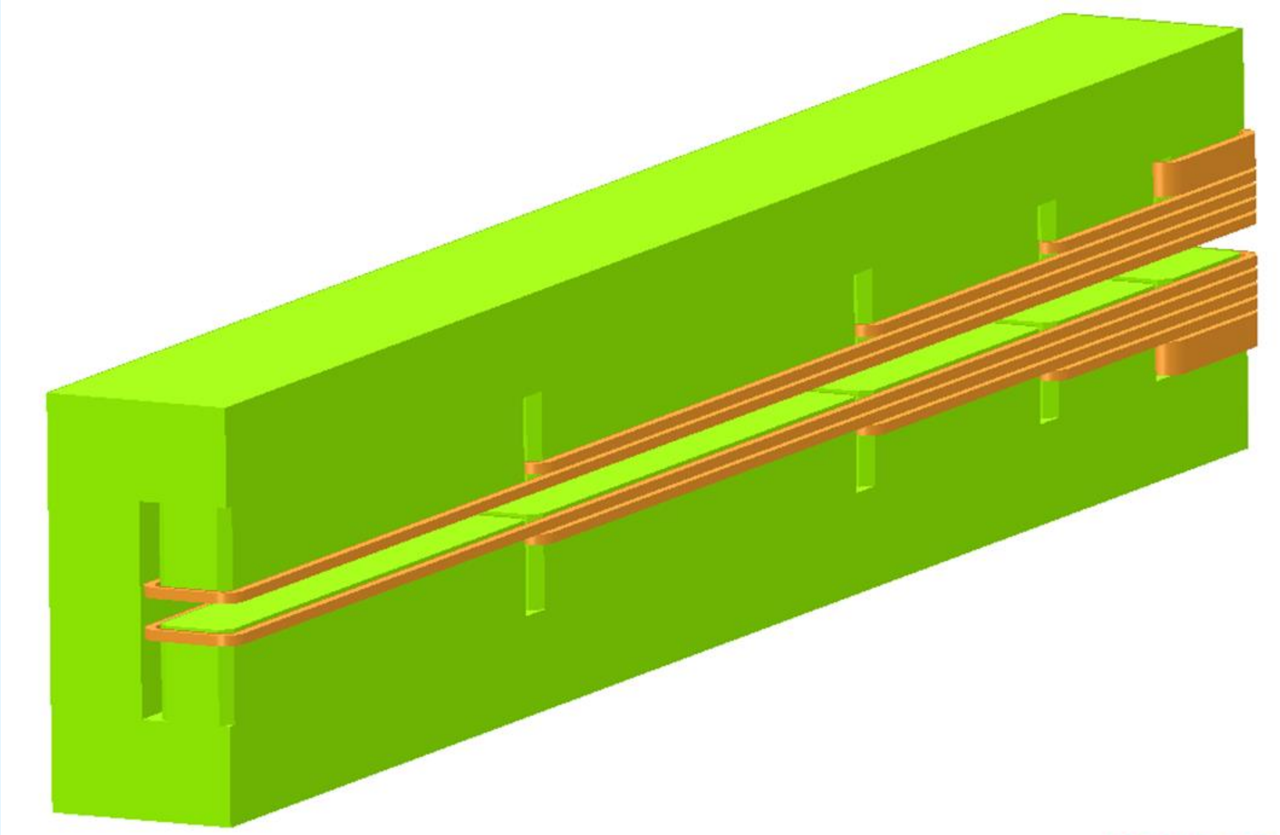


Center integrated field is 0.508 T-m at 13240 A total coil current.

(Courtesy *Vladimir Kashikhin, Fermilab*)

Prototype L-bend for APS Upgrade (B_{max}/B_{min} = 0.634 T/ 0.131 T = 4.84)

L-Bend: Varying Ampere.Turns

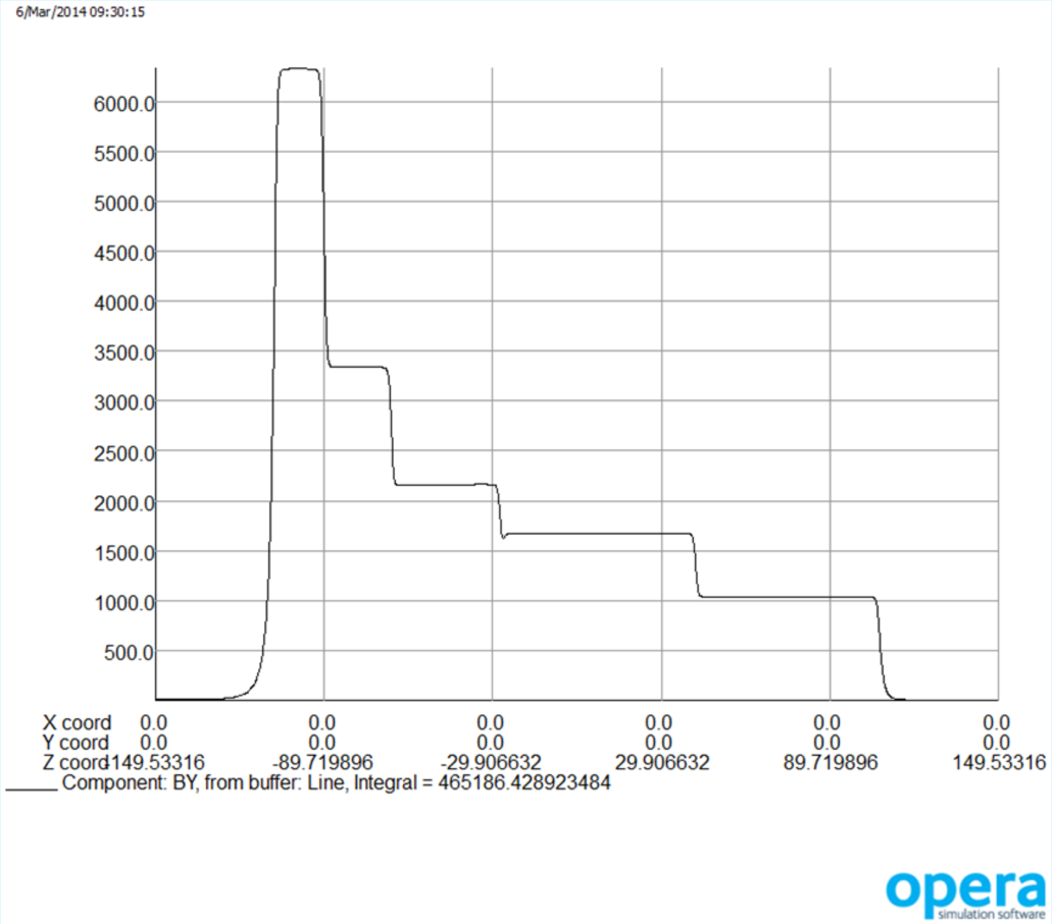


(Courtesy *Mark Jaski*, *APS Upgrade*, *Argonne*) opera simulation software

Alternate L-bend design for APS Upgrade (Constant gap)

ESRF is developing a permanent magnet based design (Le Bec et al., LER2013)

L-Bend Field Profile: Constant Gap



(Courtesy *Mark Jaski*, *APS Upgrade*, *Argonne*)

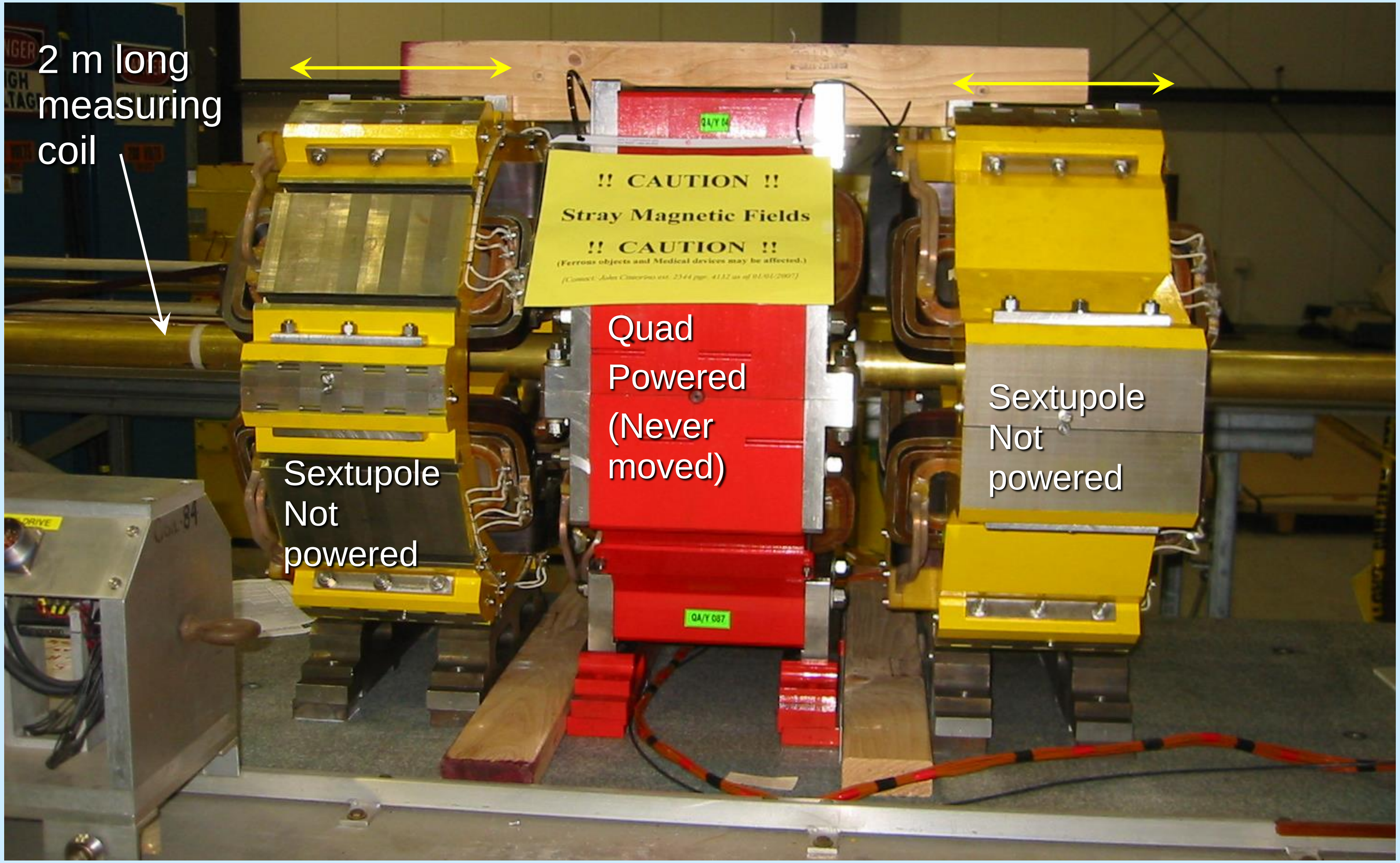
Alternate L-bend design for APS Upgrade (Constant gap)

Cross-talk between Adjacent Magnets

- Large number of magnets must be placed as close to each other as physically possible in order to maximize space available for insertion devices.
  - Main constraint is installation of vacuum and other components
- There could be effects from other magnetic components nearby.
- The fringe fields may overlap impacting the field quality.
- We will call the field quality impact of placing magnets close together as the “cross-talk”
  - Impact on the Integrated field strength
  - Impact on the field harmonics

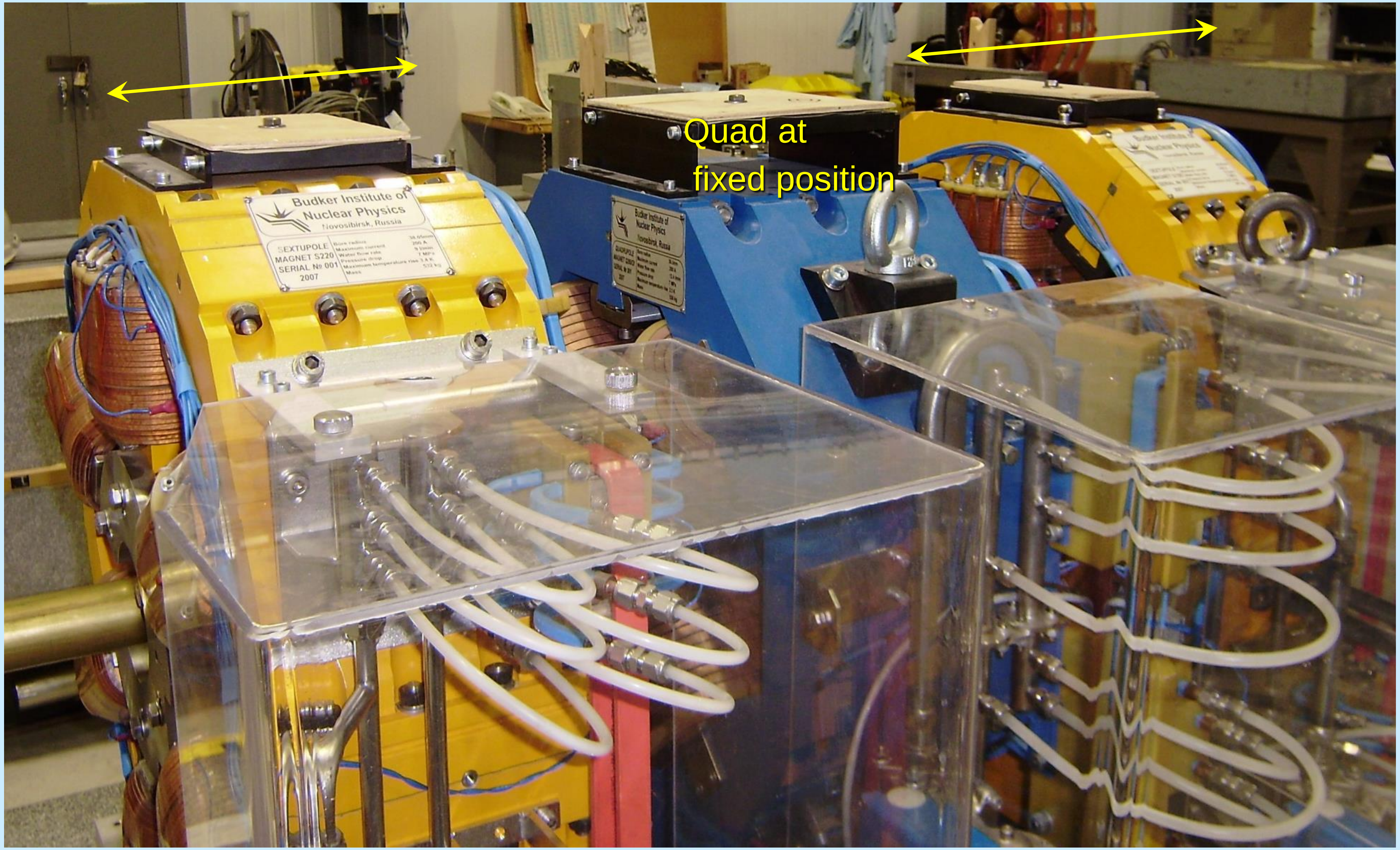
SLS Quadrupole between Sextupoles

Measurements at BNL: Minimum Yoke-to-Yoke gap = 136 mm

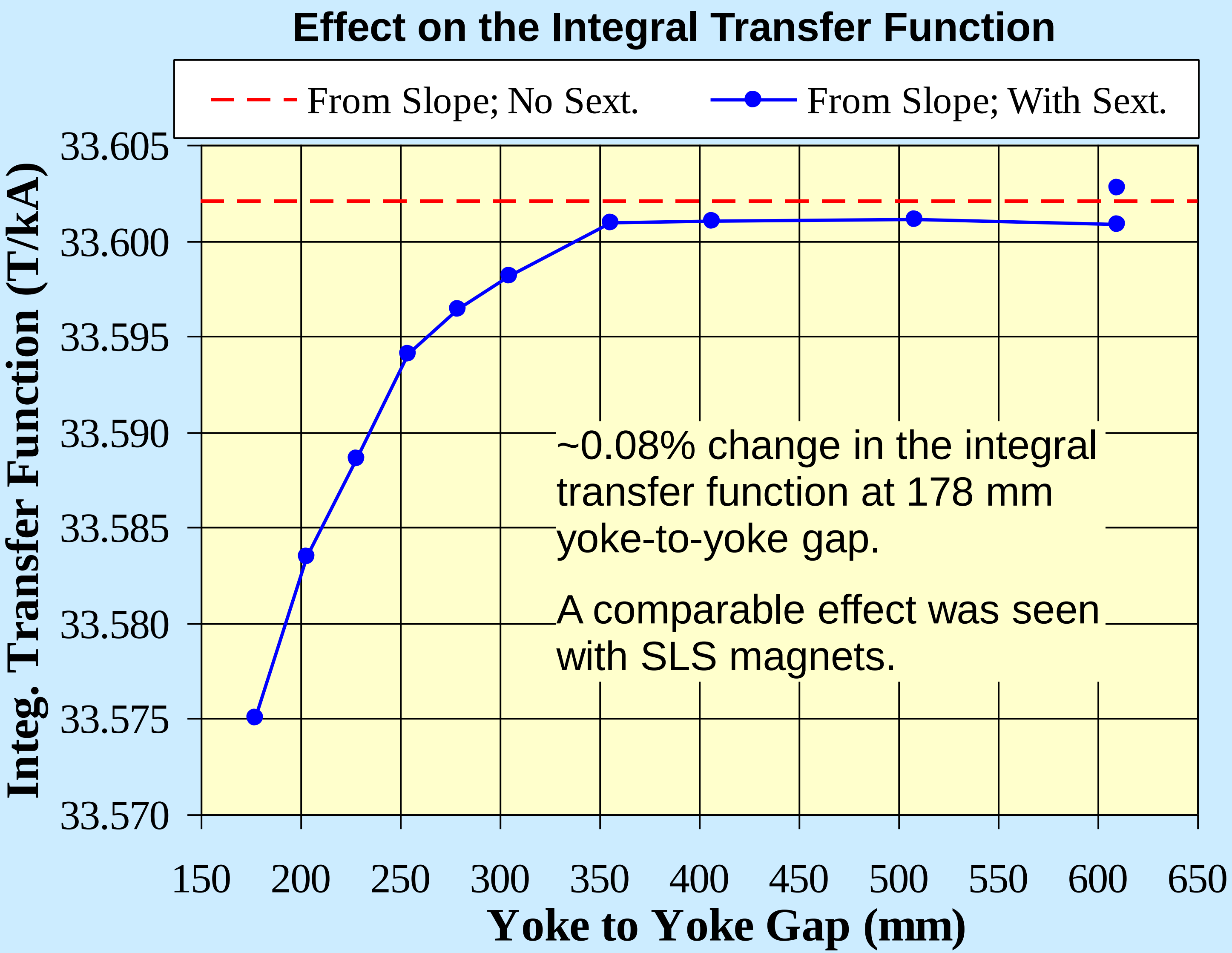


ALBA Quadrupole between Sextupoles

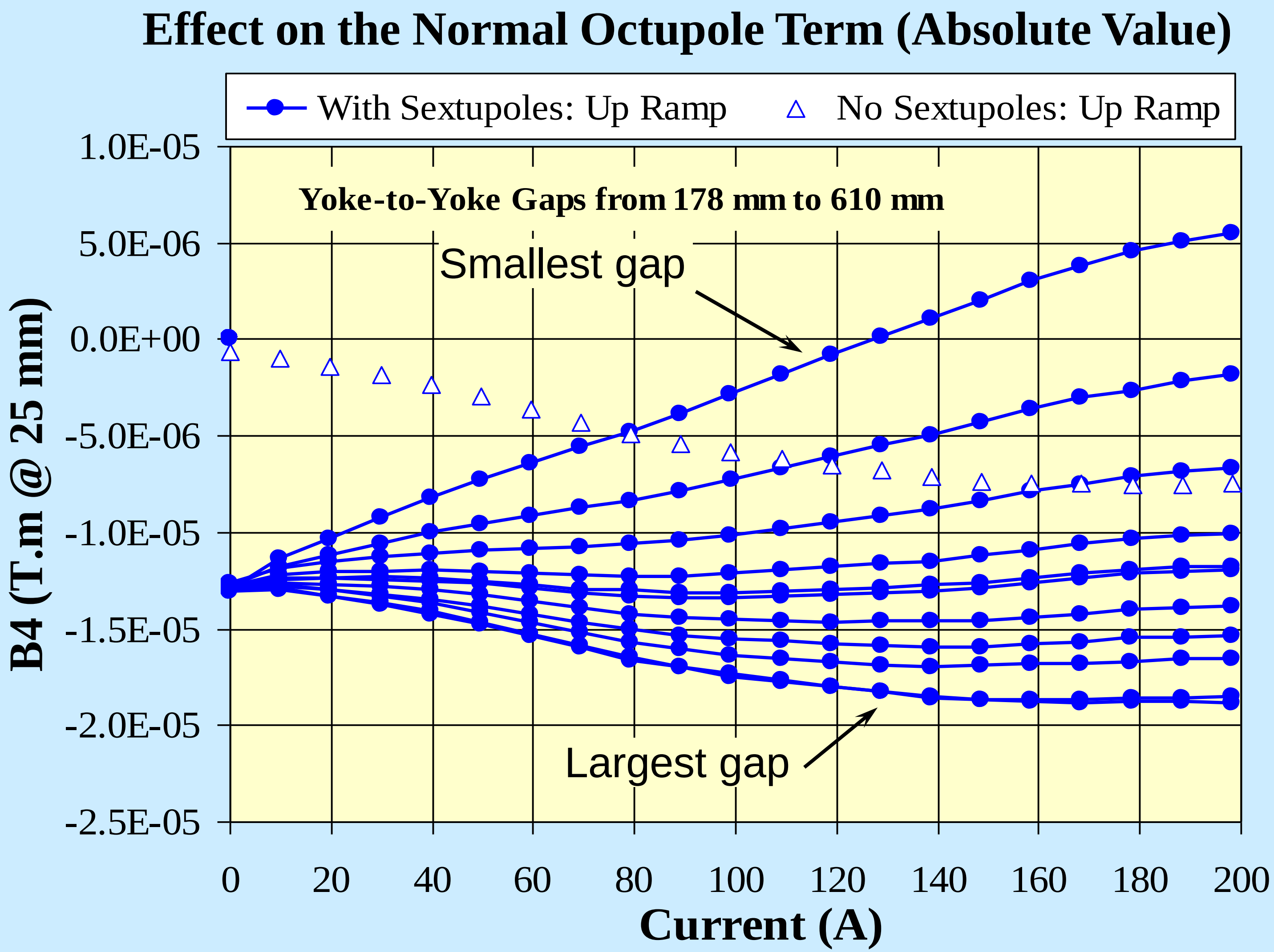
Measurements at BNL: Minimum Yoke-to-Yoke gap = 178 mm



ALBA Quadrupole between Sextupoles

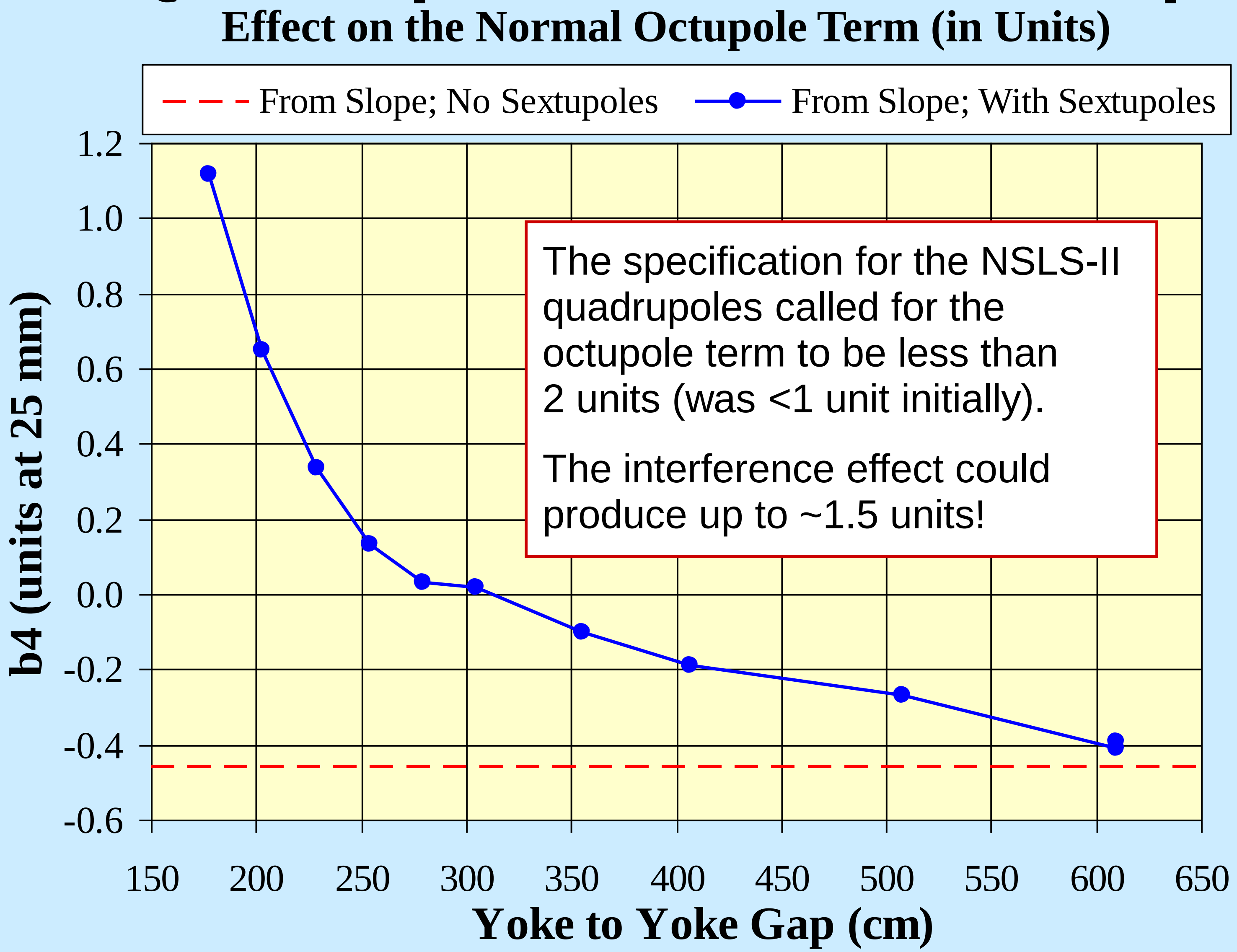


ALBA Quadrupole between Sextupoles

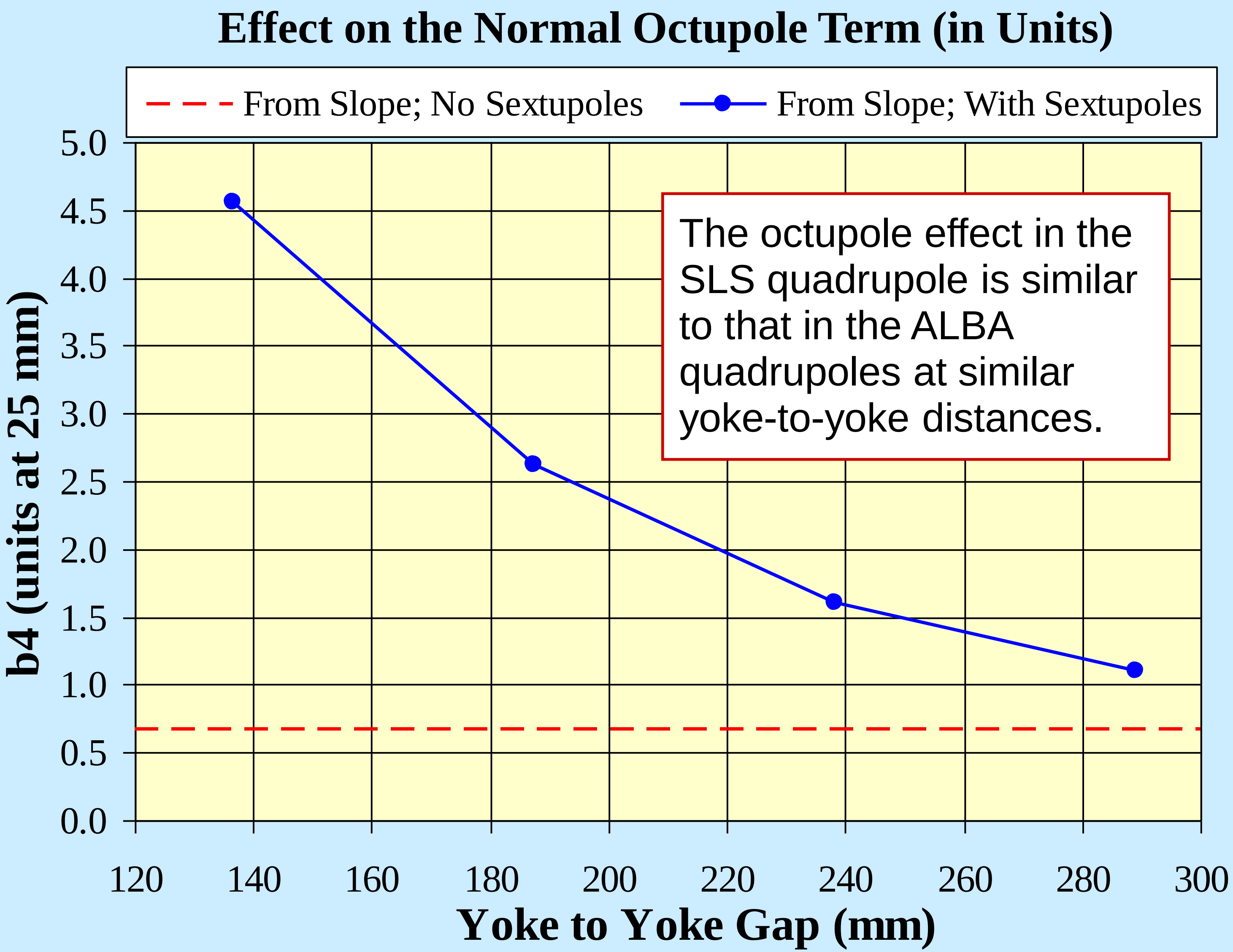


There is a clear change in the slope of the curve as the gap is reduced from 610 mm to 178 mm.

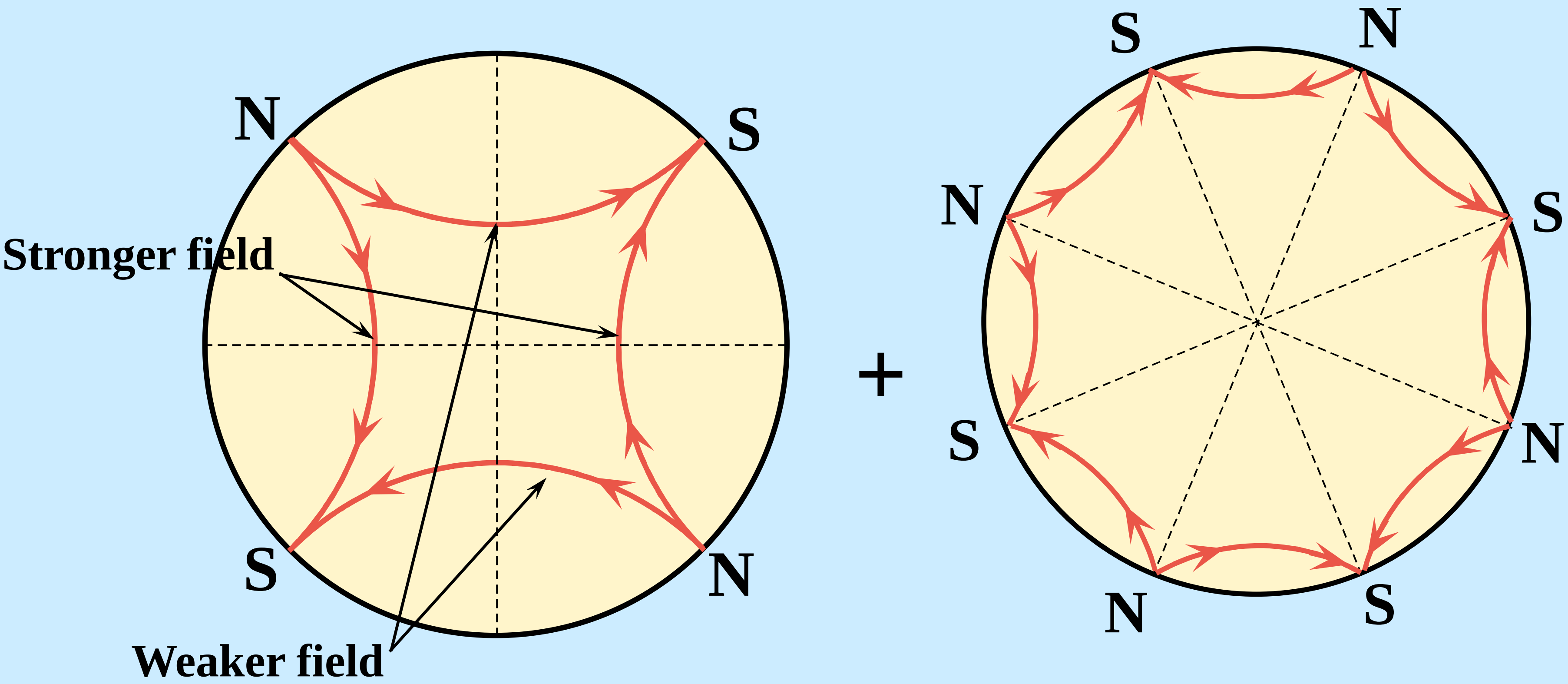
ALBA Quadrupole between Sextupoles



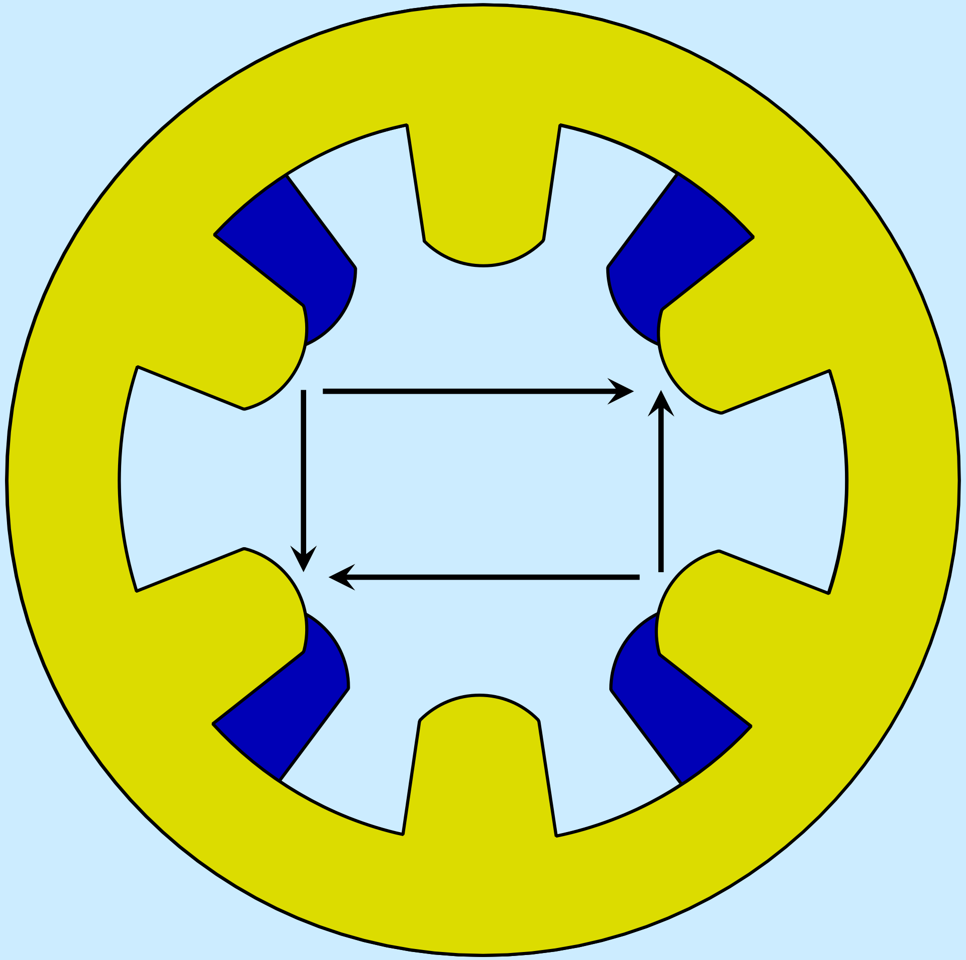
SLS Quadrupole between Sextupoles



Positive Normal Octupole in a Quadrupole



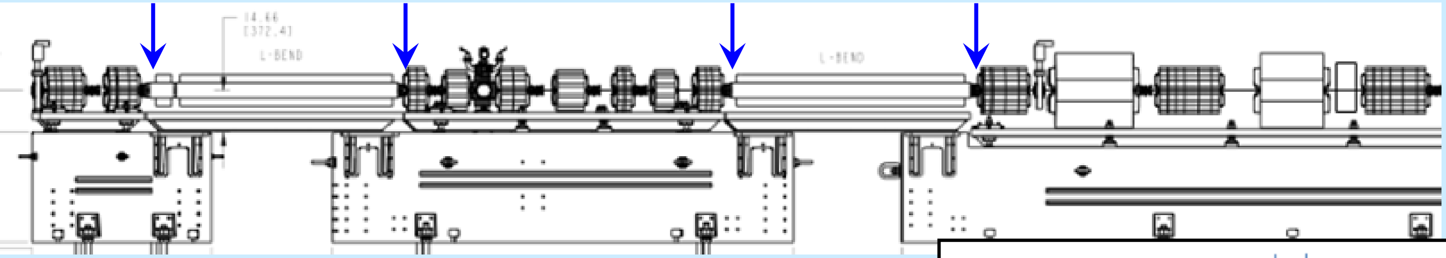
Quadrupole Powered near Sextupole Iron



It is plausible that some flux jumps over to the sextupole poles near the midplane and drives the sextupole yoke with a quadrupole field symmetry. This would result in a slightly weaker horizontal field as compared to the vertical field, resulting in a positive octupole term.

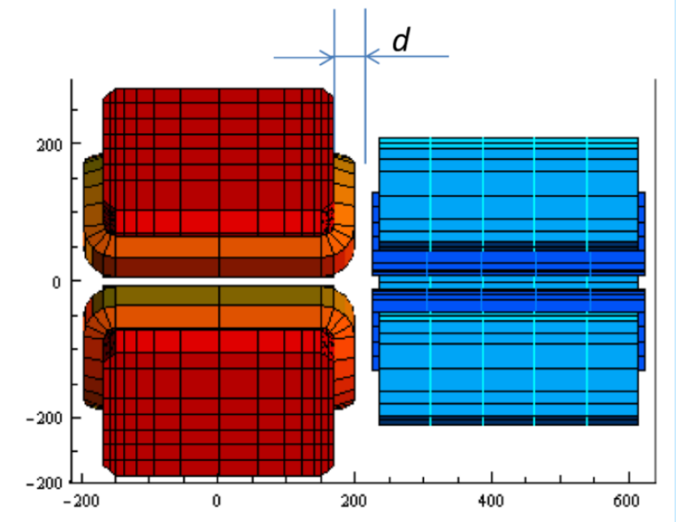
Cross-talk: Quadrupole near a Dipole

- APS upgrade lattice, for example, has quadrupoles very close to the longitudinal gradient dipoles (~60-80 mm clear gaps).



The cross-talk in a similar situation is studied by Le Bec, et al. for the case of ESRF upgrade magnets.

(Le Bec et al., LER2013)



High gradient quadrupole and PM dipole. Distance between yokes is *d*.

Cross-talk: Quadrupole near a Dipole

Integrated field errors

Quadrupole magnet

- Bore radius 12.5 mm
- Length: 335 mm, gradient: 100 T/m

Dipole magnet

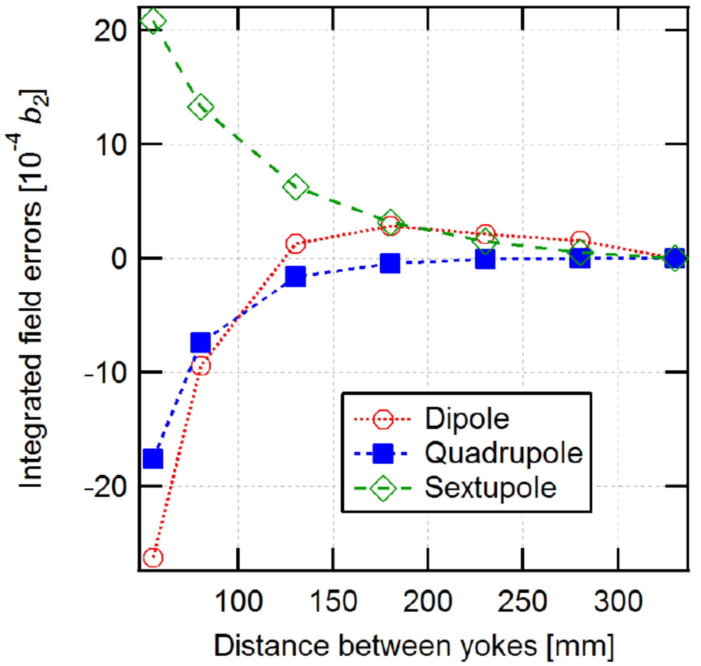
- Vertical aperture 22 mm
- Length: 400 mm, Max field: 0.65 T

Impact @ d=100 mm

- Quad. centre displacement: 4 μm
- Quadrupole decreases by 0.05 %
- Parasitic sextupole: $\Delta B/B=10^{-3}$, $\Delta G/G=2\ 10^{-3}$

Impact @ d=55 mm

- Quad. centre displacement: 20 μm
- Quadrupole decreases by 0.2 %
- Parasitic sextupole: $\Delta B/B=2\ 10^{-3}$, $\Delta G/G=4\ 10^{-3}$



Integrated field errors due to the crosstalk between a dipole and a quadrupole. Normalization by the quadrupole integrated field at ρ = 7 mm.

(From *G. Le Bec et al., Low Emittance Rings Workshop, July 8-10, 2013, Oxford.*)

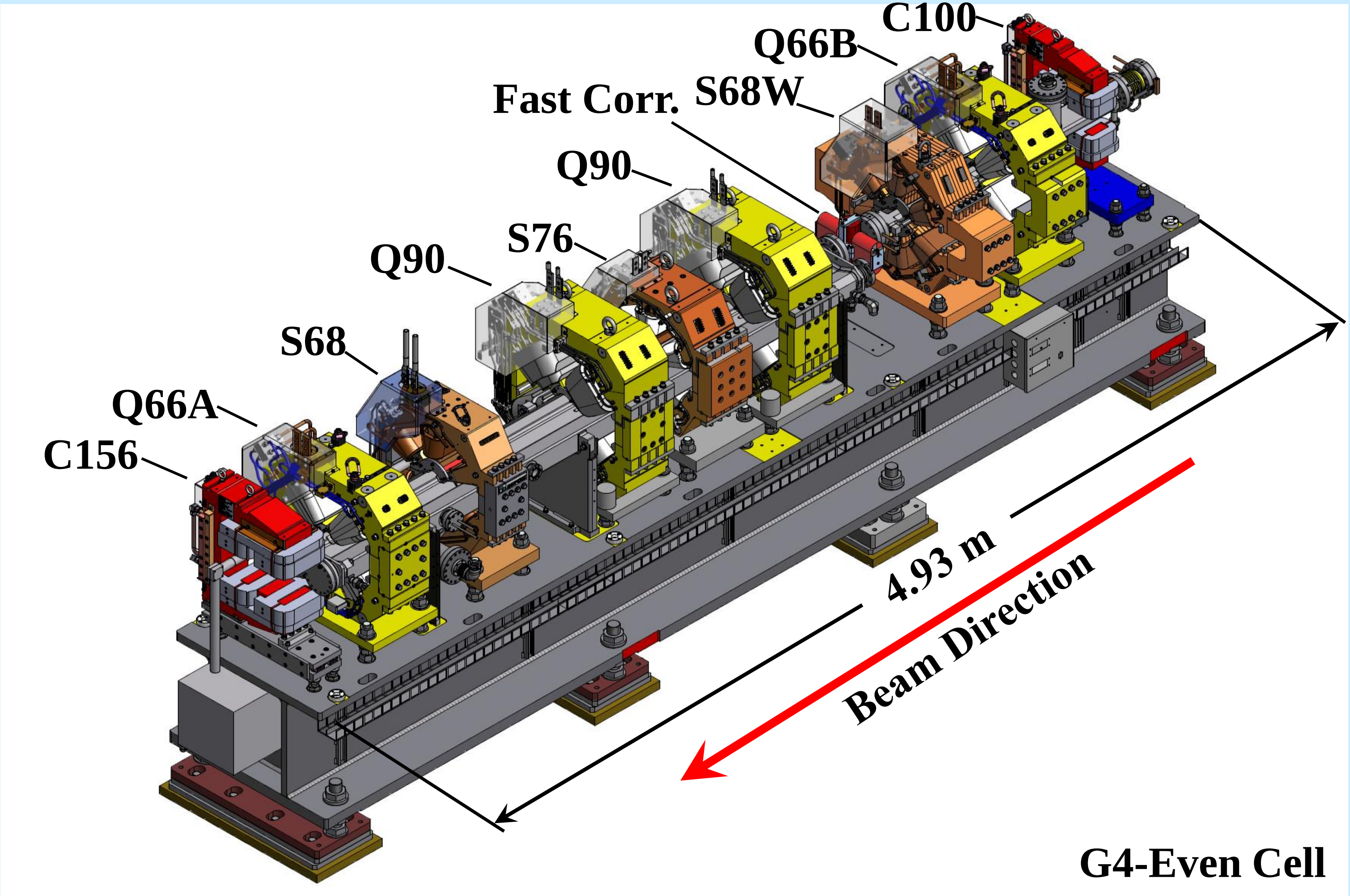
Alignment Between Magnets

- Typical alignment requirement for a subgroup of magnets within a lattice cell is ~ 30 μm RMS. Such a group of magnets is usually assembled into a single unit on a common support, such as a girder.
  - Example: NSLS-II had 90 girders with 6 or 7 multipoles on each
- A unit cell may contain several such "girders". The "girder-to-girder" alignment tolerance is typically ~ 100 μm RMS. This can be achieved by survey, provided the "girders" are characterized.
- Several different approaches have been used to precisely align magnets on a "girder". The alignment requirements and scheme can affect the design and assembly of the magnets.

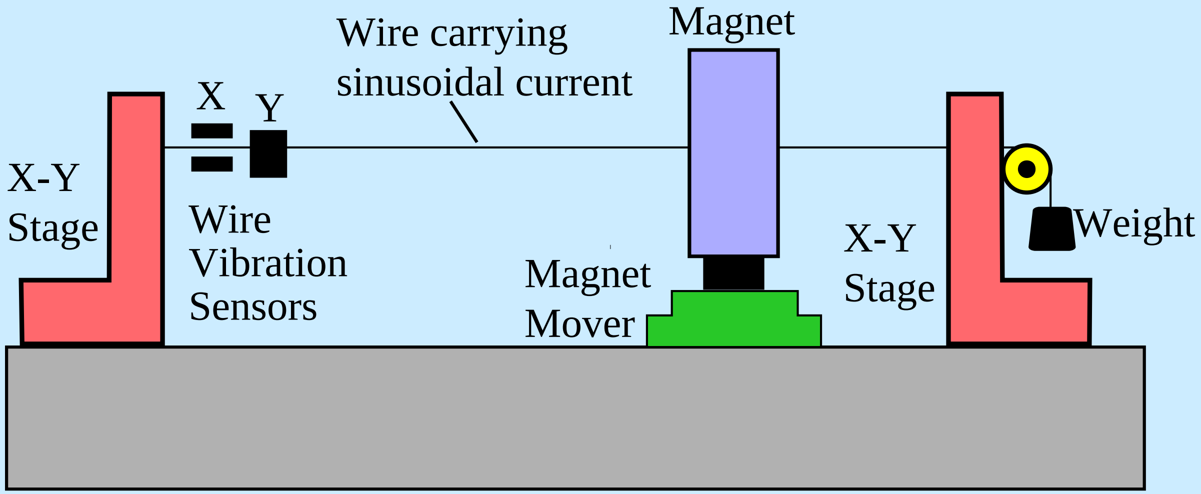
Alignment Based on Magnetic Measurements

- Conventional approach to magnetic alignment is to locate the magnetic axis of every magnet by magnetic measurements, and then use this information to align a group of magnets.
  - Rotating coil measurements, or wire based techniques
  - Survey to relate magnetic measurement probe to fiducials
  - Stack up of errors can be large, and may exceed 30 μm RMS
- Another approach is to install magnets on a support structure ("girder") without fiducializing, and align them to each other directly using a wire based magnetic measurement
  - Vibrating wire (e.g. used for NSLS-II) or stretched wire
  - Can achieve high alignment precision (<10 μm RMS)

Example of a NSLS-II Girder

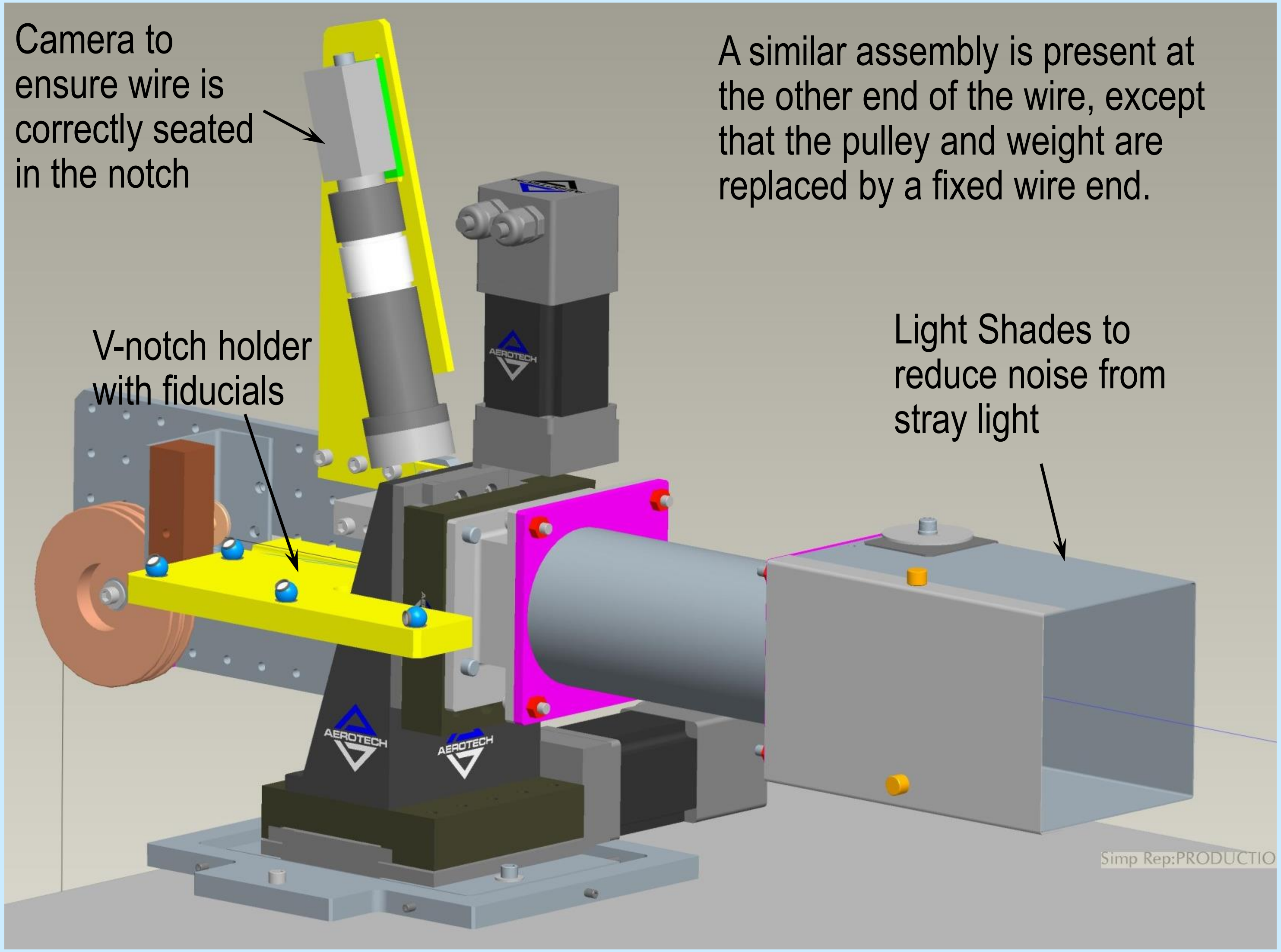


The Vibrating Wire Technique: Basics

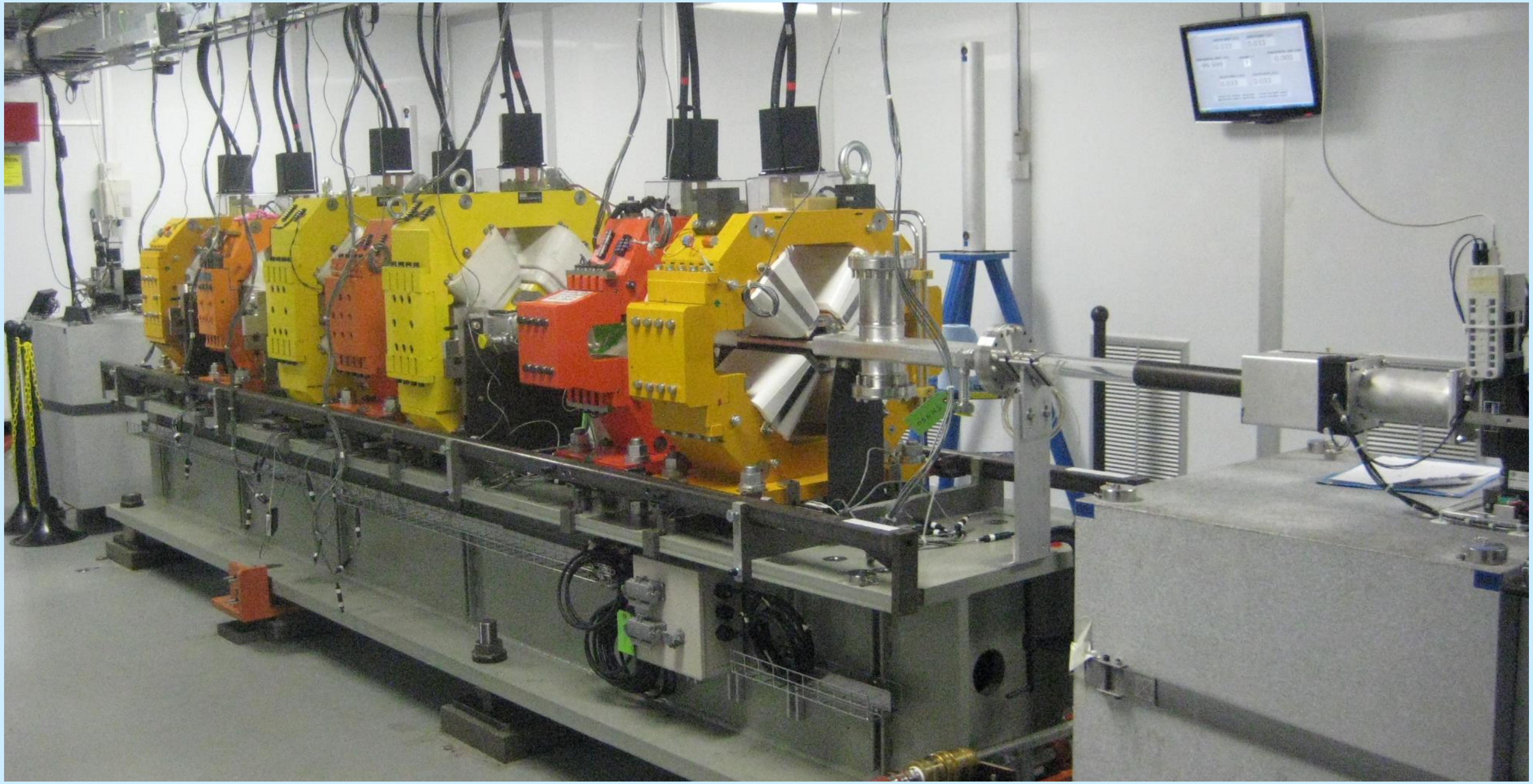


- An AC current is passed through a wire stretched axially in the magnet.
- Any transverse field at the wire location exerts a periodic force on the wire, thus exciting vibrations.
- The vibrations are enhanced if the driving frequency is close to one of the resonant frequencies, giving high sensitivity.
- The vibration amplitudes are studied as a function of wire offset to determine the transverse field profile, from which the magnetic axis can be derived.
- Resonant mode must be chosen carefully to match magnet axial position.

Complete Wire Mover Assembly



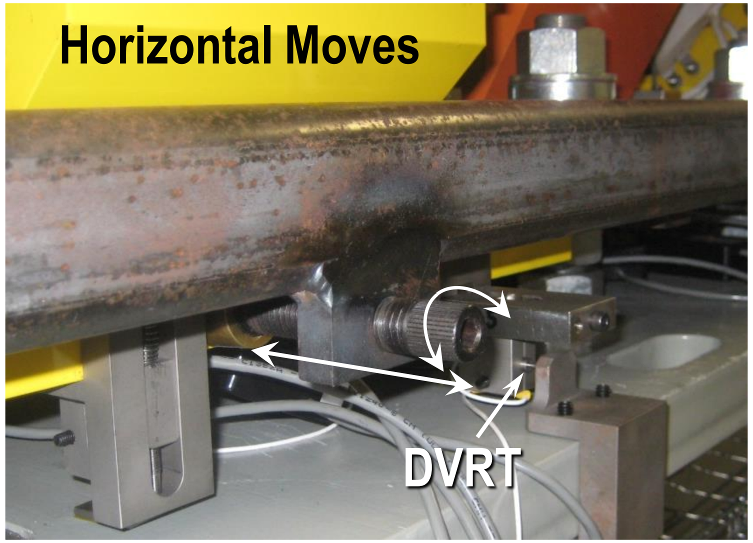
A NSLS-II Girder Undergoing Alignment

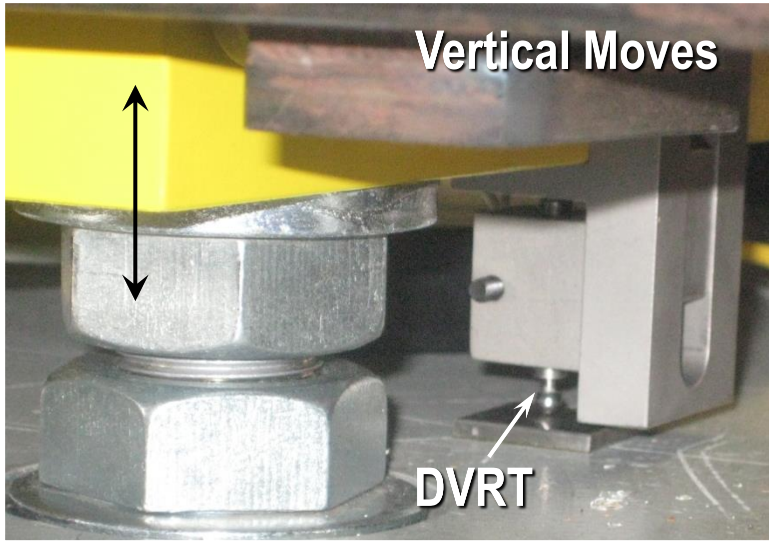


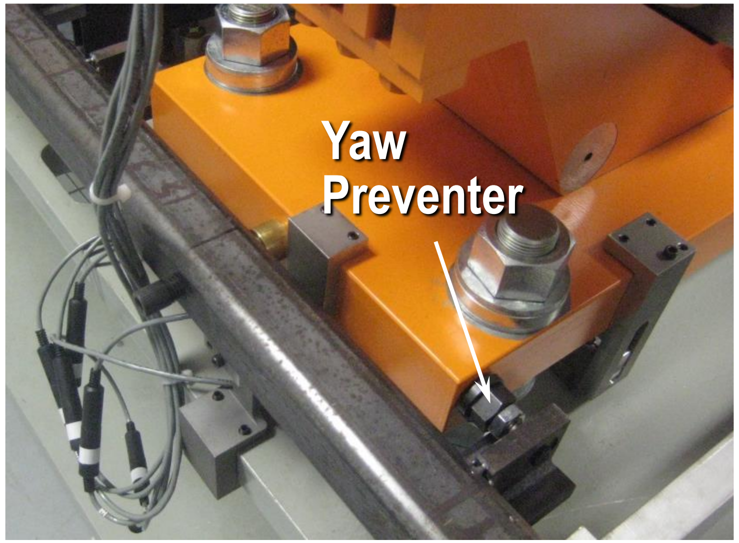
Moving Magnets to Desired Position

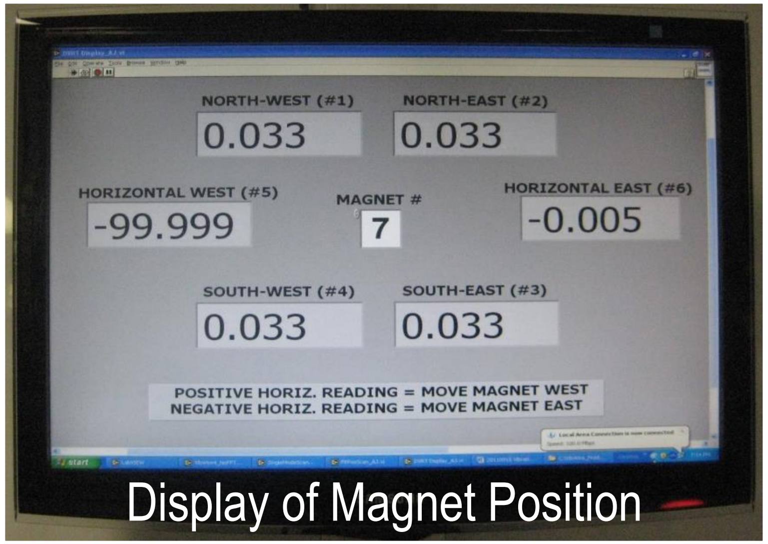
- Each magnet sits on a thick base plate, mounted to the girder using four bolts.
- A set of four vertical displacement sensors (DVRTs) is attached to the four corners of the base plate. These allow monitoring of the vertical position, and also help in controlling roll and pitch of the magnet.
- One horizontal displacement sensor is also mounted to the base plate. This does not allow monitoring of yaw. The yaw is maintained by yaw preventers present in a temporary fixture on the girder. (Ideally, sensor should be located at midplane.)
- The displacement sensors are initialized to the magnet position relative to the chosen “best-fit” line, based on vibrating wire measurements. The vertical and horizontal positions of one selected magnet at a time are displayed in real time on large monitor screens on the walls on both sides of the girder.
- Magnets are moved manually using mounting nuts for the vertical adjustment and a pair of adjustment screws in the temporary fixture for horizontal adjustment. *This has to be done in small torque increments and in small moves at a time*.

Adjusting Magnet Position

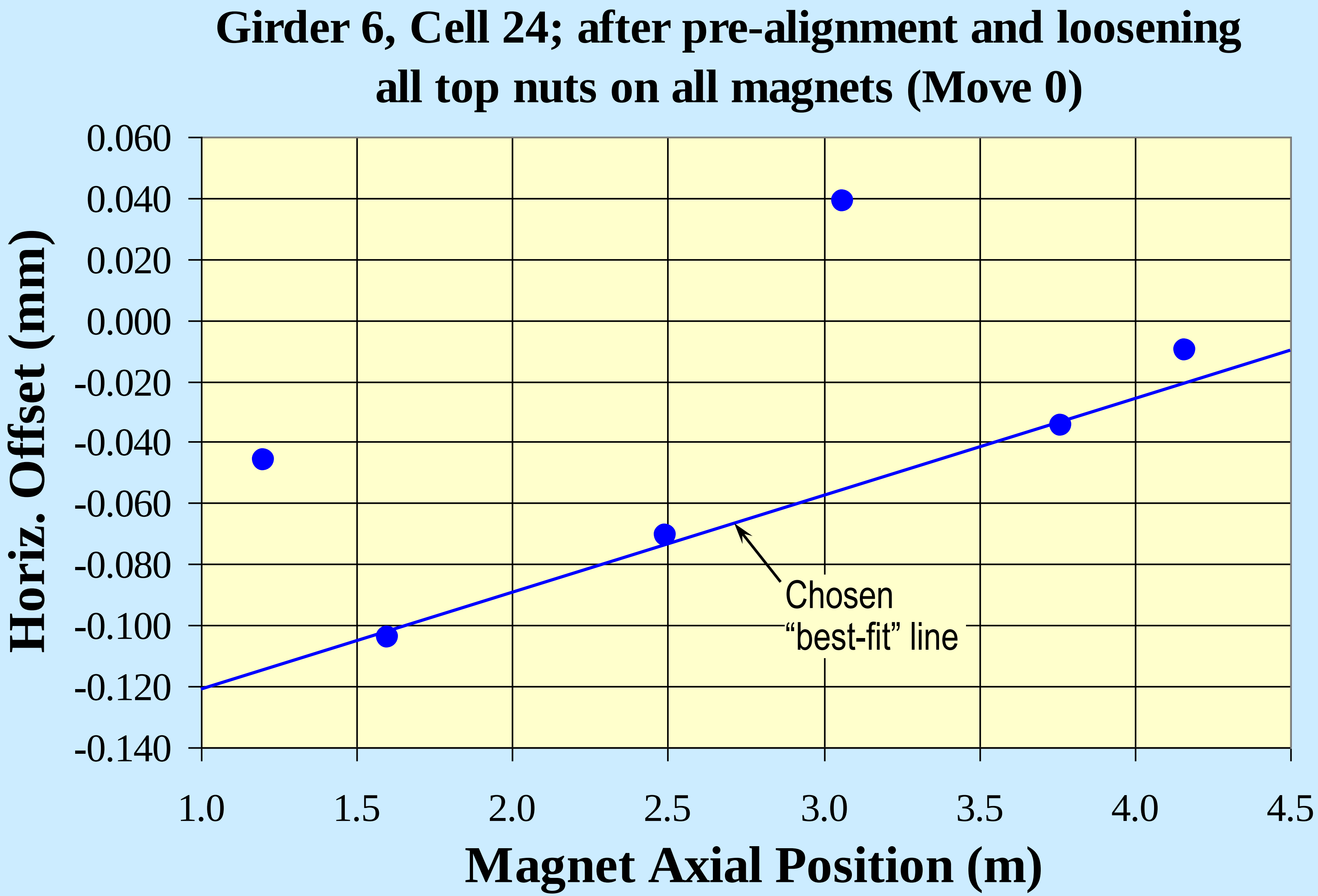




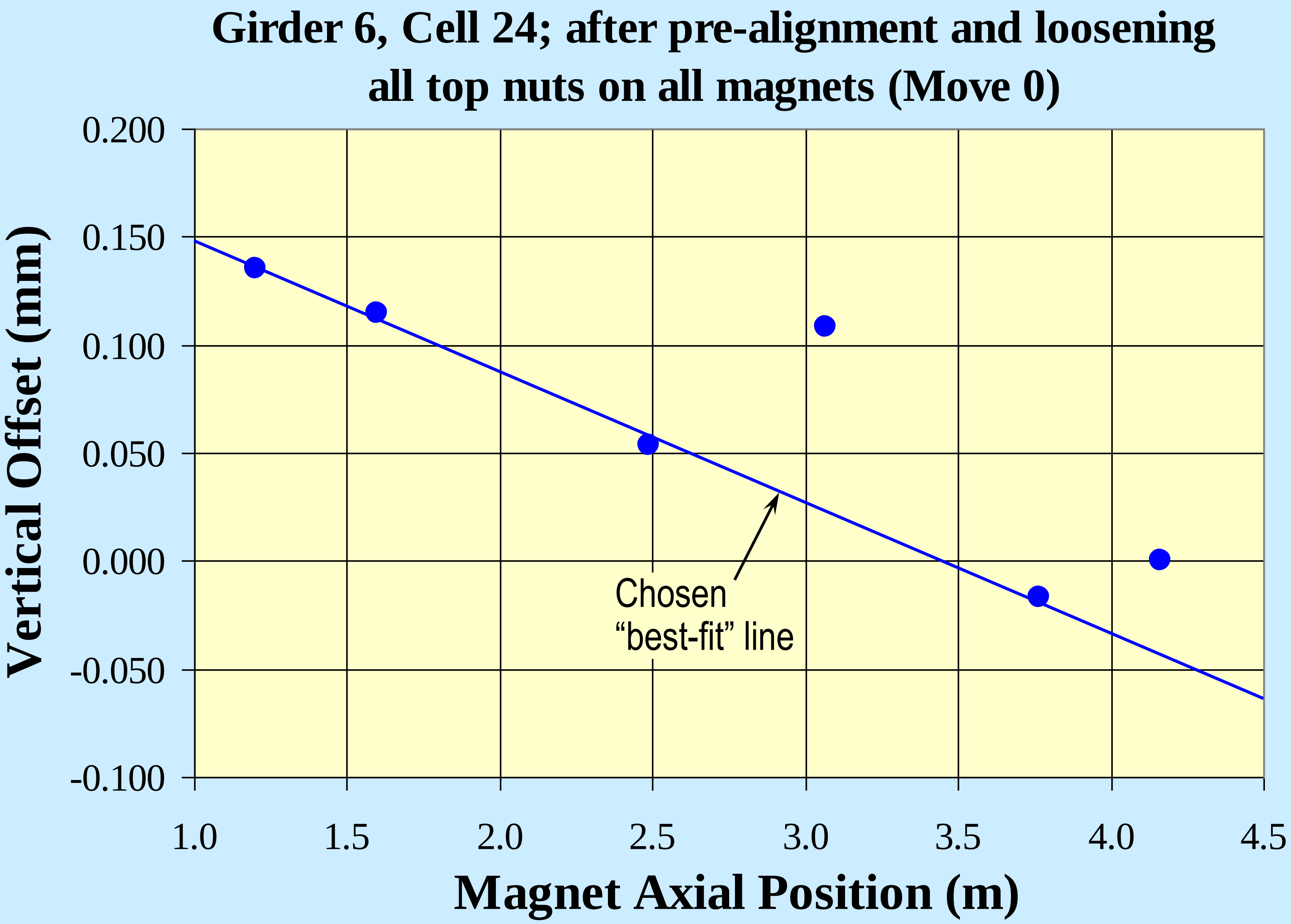




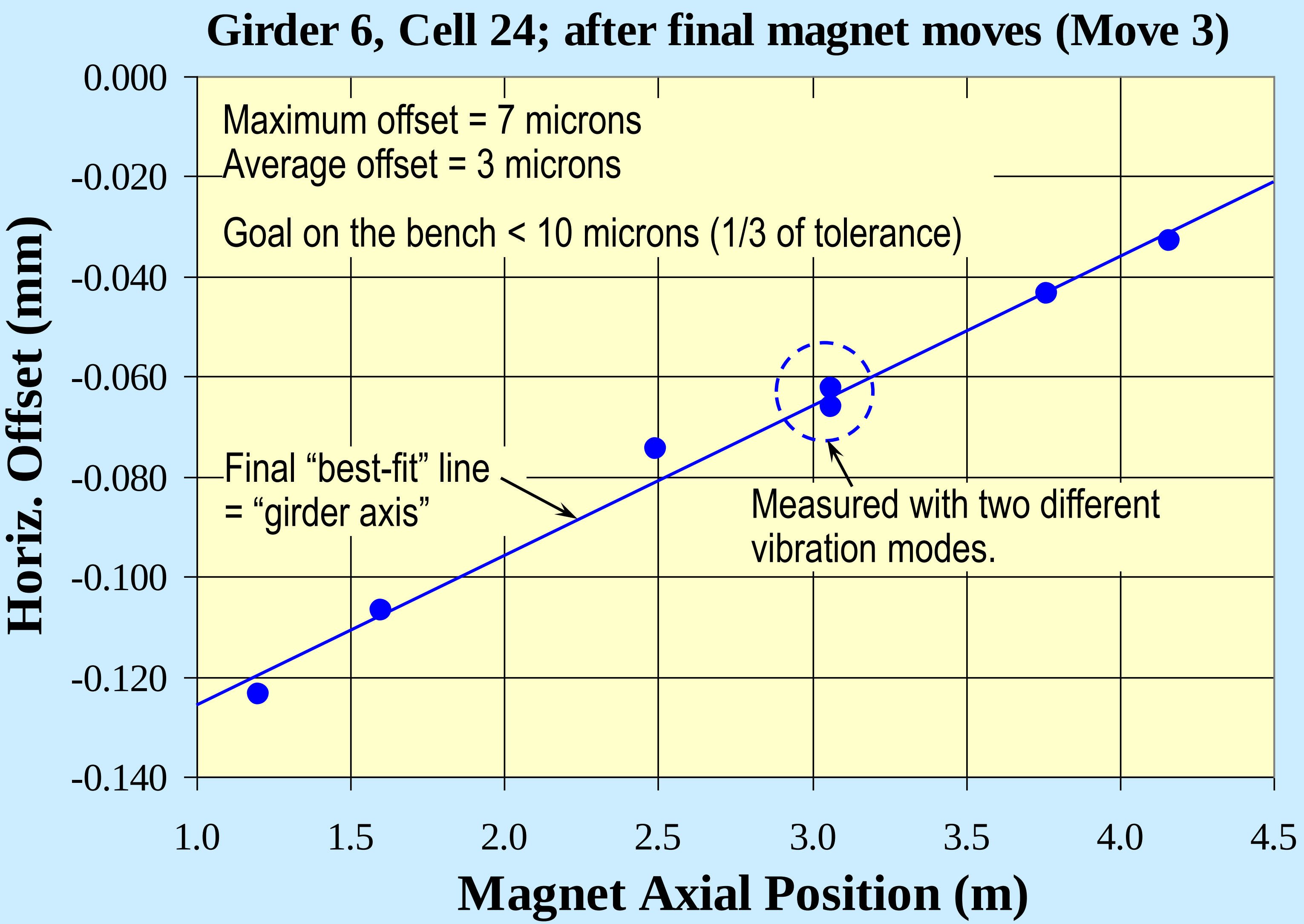
Example: Before Final Alignment



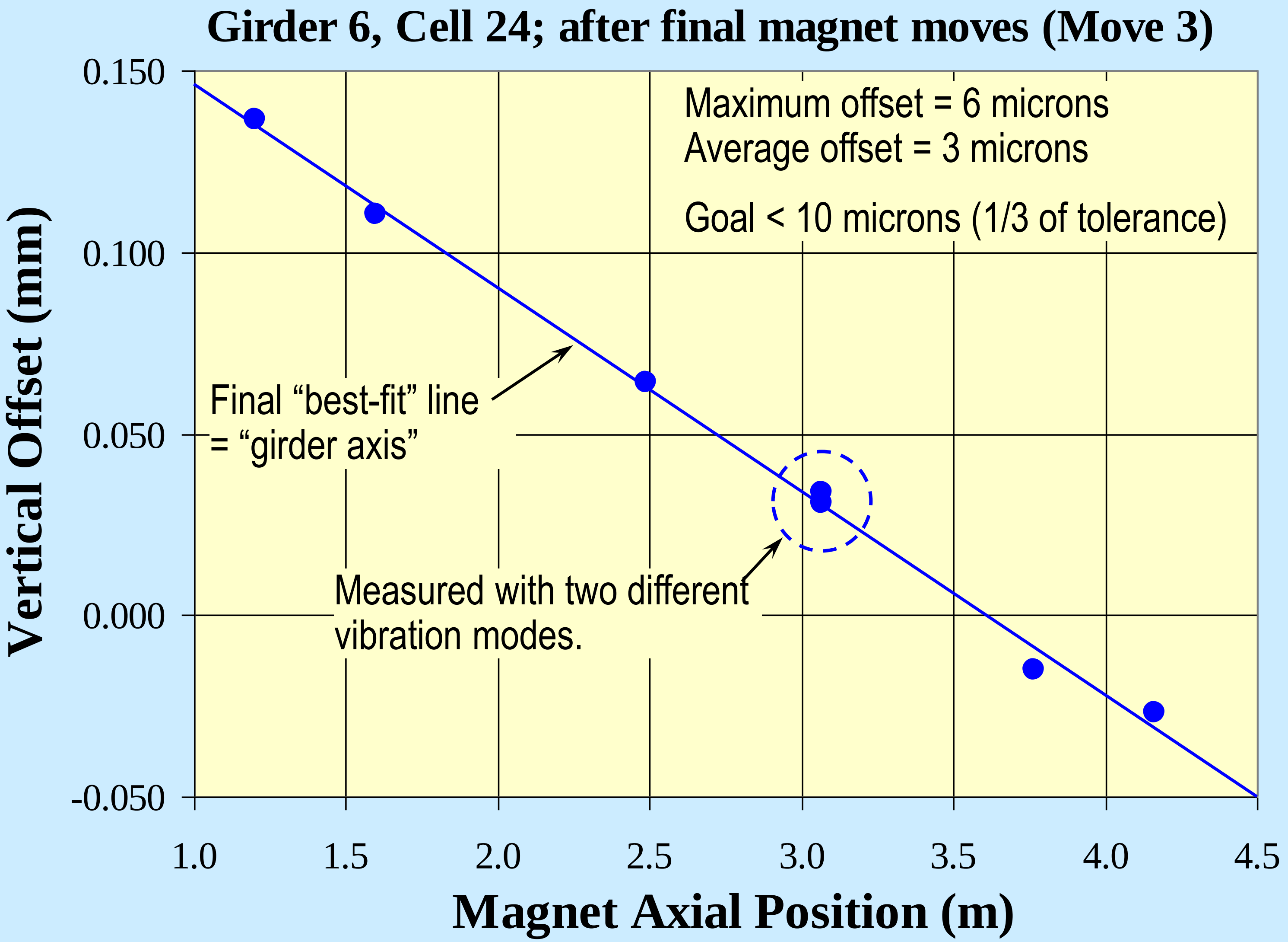
Example: Before Final Alignment



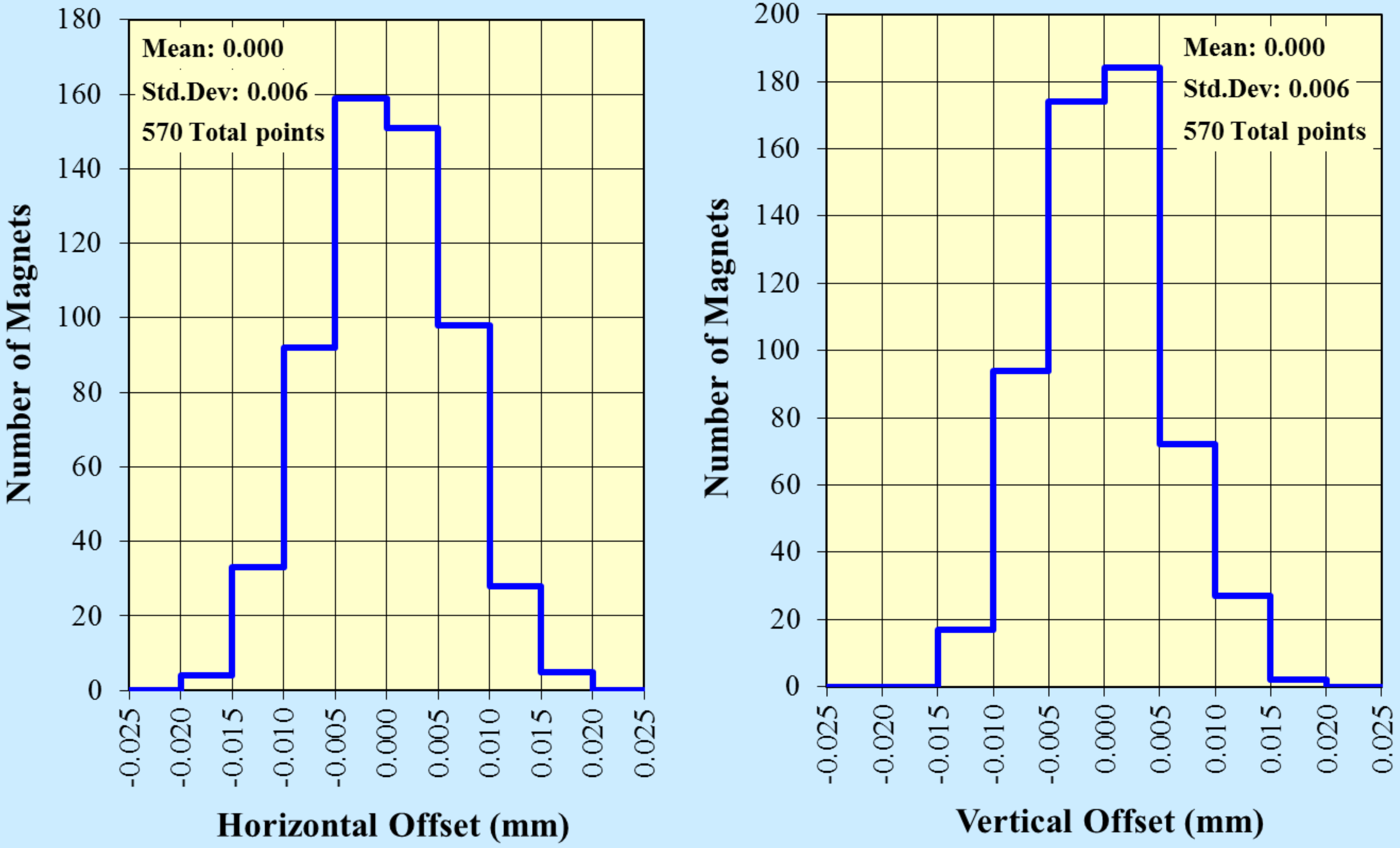
Example: Final Alignment - Horizontal



Example: Final Alignment - Vertical



Summary of Magnet Offsets in NSLS-II



Summary of Magnetic Alignment

- Magnetic alignment provides the best assurance that magnets are aligned to the required tolerance, or better.
- Direct alignment using a wire based technique saves the effort to fiducialize individual magnets and avoids limitations due to survey error stack up.
- But there are drawbacks:
  - Measurements are time consuming (can be reduced significantly by other wire based techniques, such as a rotating wire).
  - Moving magnets precisely and securing them to the girder requires small moves, and could be time consuming for large moves.
  - Girder profile must be reproduced for over-constrained installation.
  - Readily applicable to straight assemblies only.

A Novel Approach to Alignment

- A novel approach to magnet fabrication and alignment has been proposed by Maxlab and used for the upcoming Max-IV.
- The idea is to fabricate a group of magnets as a single block, with the magnets sharing a common iron yoke made out of a single solid block of iron. (Typical length ~2.3 m to 4.5 m)
- The method relies *solely* on tight machining and assembly tolerances, assuming that the mechanical and magnetic centers may be considered essentially the same.
- The entire solid block is treated as a single rigid object, with magnets aligned to each other by construction, thus reducing magnetic measurement, alignment, and installation effort.

See *M. Johansson, et al., J. Synchrotron Rad. (2014),* ***21****, 884-903*

Example of a Max-IV Assembly

- Dismountable at horizontal midplane.
- all yoke parts = Armco low carbon steel.
- Quad and corr pole tips mounted over the coil ends.
- 6-pole and 8-pole magnet halves mounted into guiding slots in yoke block.
- Electrical and water connections located towards inside.

Based on M. Johansson, *Workshop on Accelerator R&D for Ultimate Storage Rings*, Huairou, Beijing, China, Oct 30-Nov 1, 2012.

Pros and Cons of Max-IV approach

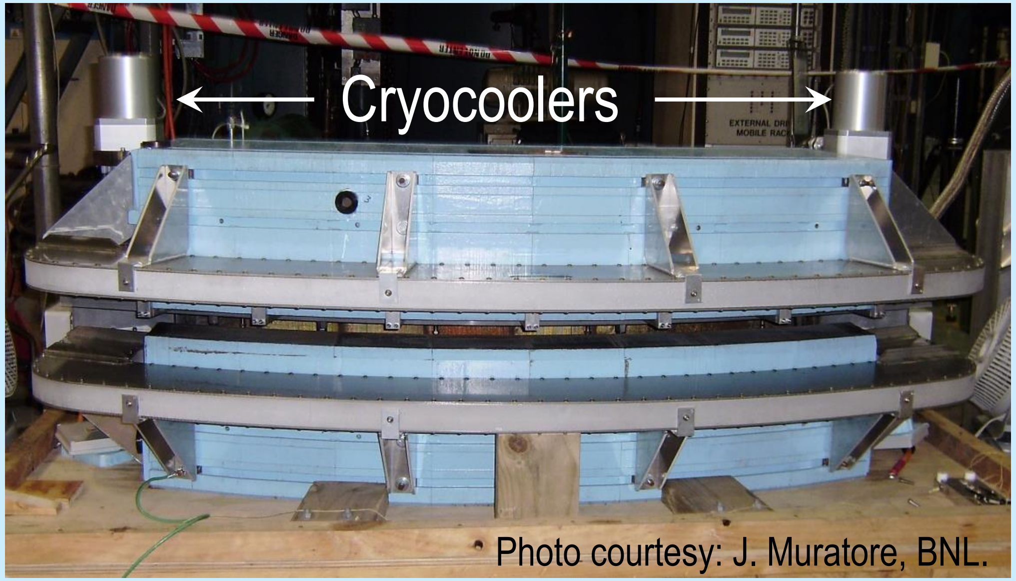
- There are several attractive features:
  - No assembly and alignment onto girders is needed. The entire assembly is delivered as one unit by industy, ready for installation.
  - Significant savings in installation (cost, schedule)
  - No need for individual magnet supports and adjustments, so magnets could be placed closer to each other (subject to other limitations).
  - Production data from Max-IV shows that all specifications are met.
- There are a few potential drawbacks:
  - Ability to precisely machine large objects to the required tight tolerances may be limited to a few specialized vendors.
  - No last minute change of lattice or magnet adjustments are possible.
  - Very long assemblies may not behave as a rigid body.
  - May be more prone to cross-talk if magnets are driven to higher fields.

For the Future …

- There is a trend towards higher field strengths, smaller apertures, and restricted longitudinal space.
- Magnet designs are limited by the available current density and iron saturation in conventional designs.
- It is possible to overcome limitations of conventional room temperature magnets with superconducting magnets:
  - Current density can be increased by a factor of 100 or more
  - Field could be predominantly conductor dominated, rather than iron dominated (e.g. in hadron machines)
  - Use of high temperature superconductors (HTS) could keep cost of cryogenics low (power cost ~ 1/3 of copper coils)

A NSLS Dipole Fitted with HTS Coils

Spare VUV ring dipole from NSLS showing the original copper coils



Coils were replaced with HTS coils by HTS-110 Ltd, New Zealand, and the magnet was tested at BNL.

J. Muratore, et al., Proc. ASC2010, in IEEE Trans. on Applied Superconductivity, Vol. **21,** No. 3, 1653-6 (June 2011).

Summary

- Magnets are used in storage rings for bending and focusing the particle beam.
- The field in the aperture of a magnet may be described in terms of a few harmonics, instead of a point-by-point map.
- Symmetries in the magnet geometry result in allowed and unallowed harmonics. Harmonics may help diagnose errors.
- Magnet design process involves achieving the required field strengths while respecting all other physical constraints.
- Requirements for upcoming low emittance storage rings are pushing the limits of conventional magnet designs, leading to some innovative solutions.

Some Useful References

- Proc. CERN Accelerator School on Magnets, Bruges, Belgium, 16-25 June 2009, CERN Report CERN–2010–004
(30 Nov 2010).
  - Many good articles on physics and engineering of magnets.

- *Iron Dominated Electromagnets – Design, Fabrication, Assembly and Measurements*, J. Tanabe, SLAC-R-754
(June 2005)

- *Field Computation for Accelerator Magnets: Analytical and Numerical Methods for Electromagnetic Design and Optimization*, by Stephan Russenschuck (Wiley).